SPECIAL BULLETIN 353 (First Revision) JULY 1953

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Diagnosed By

Plant Symptoms
Tissue Tests
Soil Tests

By R. L. Cook and C. E. Millar

AGRICULTURAL EXPERIMENT STATION
Department of Soil Science
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Plant Nutrient Deficiencies Diagnosed by Plant Symptoms, Tissue Tests and Soil Tests

By R. L. COOK AND C. E. MILLAR

A HALF-CENTURY AGO, soil chemists were seeking the answers to fertility problems by complete chemical analyses of soils. It seemed that by comparing the percentages of the various nutrient elements in an unproductive soil with corresponding figures for a normal productive soil it would be possible to see at once what was lacking in the unproductive soil. The problem was not that simple. Crops did not always respond to applications of different nutrients as was predicted from the chemical analyses.

Chemists then turned to a study of the composition of plants themselves. They reasoned that a shortage of some nutrient in the soil would result in starvation of the plant for that nutrient and a plant would be produced which contained an abnormally small percentage of that element.

Their efforts were largely unsuccessful for several reasons, some of which follow: The procedure was based on the assumption that plants took the different nutrients from the soil in the proportion in which they were needed for normal growth. It is now well known that this is not true and that a plant may take in a much larger amount of certain nutrients than it needs if the supply in the soil permits. Also a limited supply or excess of one nutrient may materially affect the quantity of another nutrient which is taken in by the plant. Furthermore, some plants will not show a low percentage of a certain nutrient if the supply is limited, but will merely make

the amount of growth which the supply of the nutrient permits keeping the chemical composition of the plant tissue approximately constant. This is especially true of the seeds of most crops. Other portions of plants, however, may vary in their content of certain nutrient elements according to the supply available in the soil.

One of the oldest and most reliable methods of determining the productivity of soils and their need for different elements of plant food is the use of field-plot experiments. This method is widely used today, and its results furnish the basis for fertilizer recommendations made for different crops by most agricultural experiment stations. The method, however, requires much time and is rather costly. It therefore cannot be used to diagnose crop difficulties on individual farms. Thus it becomes imperative that agricultural workers have some relatively quick and simple methods of measuring the productive capacity of a soil and of determining nutrient deficiencies on individual problem areas.

The use of quick soil tests, as a method of determining the level of easily available nutrients in soils, has become common during recent years. Such tests are not designed to measure the total quantities of nutrients in soils but rather those quantities which are available to plants. Relatively weak extracting reagents are selected which are designed to remove from the soil fractions of the nutrients similar to those removed by the plants. Here, of course, is the weak point in the soil-testing program. Plants vary greatly in their ability to feed on the nutrients in different chemical combinations in the soil. Thus it is almost impossible to be certain that "availability," as measured by a certain chemical test, coincides with "availability" to the specific plant under consideration. These soil tests, however, do furnish valuable information concerning readily soluble plant-food elements in the soil, and the usefulness of these methods will increase in the future.

Of more recent origin than the soil tests for available nutrients are tests made on green plant tissue. The logic behind the testing of green plant tissue is simple. Plants, like animals, tend to gorge themselves when food is plentiful. As a result they take in larger quantities of nutrients than can be immediately assimilated. When this has occurred, the tissue test for a certain element reveals its presence in a soluble form. One concludes then that the plant, at that particular time, is getting all it needs of that one nutrient element. When the tissue test fails to reveal the presence of the nutrient in soluble

form, the conclusion is that the plant is getting either just enough or too little for its growth needs and, therefore, the supply in the soil should be increased in some manner, as by applying fertilizer. Thus, the plant itself becomes a measure of the availability of the nutrient in the soil.

A more recent method of measuring the productive power of a soil is that of recognizing *plant symptoms of nutrient deficiencies,* using the appearance of the plant as an indication of the supply of nutrients in the soil. Underfed plants often grow slowly and may develop abnormally in much the same manner as do animals when certain essential ingredients are not included in their ration. Nutrient deficiencies may result in off-color of leaves, abnormally shaped leaves or stems, and sometimes in actual disintegration of various parts of the plants, including the roots. Of course, somewhat similar symptoms are sometimes brought about by damage from insects and disease or by injurious applications of insecticides or fungicides. Care must be taken to avoid confusion between nutrient deficiencies and irregularities brought about by such causes.

Nutrient shortages in the soil may be intensified by such abnormal weather conditions as drought, excessive moisture, or unseasonably low temperatures. In other words, the nutrients may be present in the soil in quantities sufficient for normal growth when conditions are ideal but not sufficient during periods of adverse weather conditions.

It is the purpose of this bulletin to place in the hands of agricultural workers such illustrations and descriptive material as may make it possible for them to study and test an undernourished plant and, finally, make a correct diagnosis of the cause of the abnormal condition. Just as the physician and veterinarian must sometimes resort to tests to confirm their suspicions, so must the "plant doctor" use soil and green-tissue tests to confirm diagnoses based on visual symptoms. Tests for this purpose are referred to many times in the following pages. Directions for making the tests, using the Spurway soil-testing kit, are on page 65.

Plant Symptoms of Nutrient Deficiency

Fortunately, symptoms of nutrient deficiency tend to be similar in different plants. If this were not so, it would be rather difficult to become familiar with the symptoms as they occur in a variety of crops. Plants within a family are similar in their nutrient needs. Members of the pea family, for instance, are very sensitive to a deficiency of potassium, while those of the goosefoot and mustard families have a marked need for boron. Furthermore, certain deficiencies occur only, or at least more often, under certain soil conditions. For instance, symptoms of boron deficiency are not likely to be found in plants growing on acid soils. The same thing is true with manganese deficiency. Also, plants deficient in manganese are more likely to be found on sandy soils than on soils containing a large percentage of clay.

Sometimes more than one element may be lacking in a soil, and, as a result, a plant may show signs of starvation for two elements. In such cases the diagnosis may be difficult. Usually, however, the soil is lower, relatively, in one element than in all others. The influence of that first limiting factor then dominates the metabolism of the plant, and it shows the characteristic deficiency symptoms. The investigator should keep in mind, of course, that once the first limiting factor is eliminated by addition of the corrective fertilizer, a second limiting factor may come into play. Shortages of elements other than the one causing the deficiency symptoms may be suspected on certain types of soil. The suspicions may usually be confirmed by soil tests.

Since most cases of nutrient deficiency sufficiently severe to cause an abnormal appearance can be traced to a shortage of a single element, it seems logical to consider the symptoms by individual elements, always remembering, of course, the possibility of complications arising from a shortage of two or more elements, and the possibility that the abnormal appearance may be entirely due to disease or insect injury.

NITROGEN DEFICIENCY

Nitrogen exists in the soil largely as a constituent of organic matter. Through decomposition of the organic matter by soil organisms, the nitrogen is changed into forms available to plants, ammonia

(NH_4) and nitrate (NO_3). Many young plants are able to use ammonia, whereas most older plants prefer the nitrate form of nitrogen.

Since the decomposition of the organic matter is caused by living organisms, nitrogen availability in soil is influenced by temperature, moisture, and aeration. Thus, the supply is extremely variable.

This explains why plants sometimes are found to be starving for nitrogen on soil which is high in organic matter. This occurs generally during cold, wet seasons, sometimes during dry periods, sometimes on the most fertile soils. It is during such seasons that plants are especially benefited by the presence of easily decomposable organic material such as that from leguminous crops, and from applications of soluble nitrogen fertilizers.

On farms where nitrogen starvation is common, even during seasons which favor the activity of soil micro-organisms, attention should be directed first to the organic content of the soil. If it is found that organic matter has become depleted, it should be replenished by additions of stable manures and by the production of green manures, preferably leguminous in nature.

Nitrogen starvation may occur on soils throughout the range of acidity and alkalinity. Strongly acid soils are more likely, however, to be low in easily decomposable organic matter, because legumes do not thrive on such soils and the nitrifying bacteria may not function as efficiently as they do on soils well supplied with lime.

Nitrogen particularly affects the vegetative growth of a plant. A deficiency of the element results in stunted growth and in a loss of chlorophyl. The leaves first become light green and gradually yellow. The oldest leaves on the plant, those nearest the ground on an upright plant, are first affected. After the leaves become yellow, they die. Even after the oldest leaves are dead from lack of nitrogen, the new leaves may be dark green. This shows that when the nitrogen supply in the soil is low the new growing tissue has priority on what is taken into the plant. Eventually even the new leaves lose their chlorophyl, growth slows down, and in extreme cases the plant dies.

Corn

The "firing" of corn is probably the most widely recognized symptom of nitrogen starvation. For years farmers have considered this condition to be the result of excessive drought. It is true that dry weather accentuates the deficiency. When soil becomes very dry, conditions are less favorable for nitrification, and the nitrate which is

present is transferred with greater difficulty from the soil or the soil solution to the plant. Also, during such a period, the rate of root penetration decreases, and there is very little opportunity for the formation of the nutrient-absorbing root hairs.

When drought conditions become sufficiently severe, of course, corn will dry up and die regardless of the quantity of nitrogen available. The leaves do not turn yellow in the pattern so commonly considered as dry-weather firing, however, unless there is a deficiency of nitrogen accompanying the drought. As the supply of available soil nitrogen becomes exhausted or reaches a level too low for the demands of the corn plant, the entire plant becomes light green in color and the oldest leaf, the one nearest the ground, starts to turn yellow at the tip. The yellowing then proceeds along the leaf toward the stalk, moving faster in the midrib area and more slowly along the edges. This makes it possible to distinguish nitrogen deficiency from potassium deficiency, as in the latter the yellowing progresses faster along the edges of the leaf while the midrib remains green. The difference in the pattern of the yellowing is illustrated in Fig. 1a. As

Fig. 1a. (see color plate section, page 69)

the supply of available nitrogen in the soil continues to decrease, the second and then the third leaves are affected as the yellowing moves up the stalk and the sheaths of the lower leaves turn red. By the time the third leaf shows distinct signs of nitrogen deficiency, the first leaf has become entirely yellow and almost dead.

The corn shown in Fig. 2 illustrates very nicely what would be

Fig. 2. (see color plate section, page 70)

called serious nitrogen starvation. The entire field had taken on a lighter than normal color, and the yellowing of the leaves in the characteristic nitrogen-deficiency pattern had developed to the third leaf. According to the tissue test, there was no nitrate nitrogen in the plants at that time. Apparently the plants were assimilating the nitrate as fast as it could be taken in through the roots. Such a test is indicative of nitrogen starvation and substantiates the conclusion drawn from the symptoms.

The two corn fields shown in Fig. 3, which were located in Cass

Fig. 3. (see color plate section, page 70)

County, were photographed on August 23, 1944. The fields were on the same farm and were planted by the same man. There was no appreciable difference in soil type in the two fields. The corn in the left field was planted after clover which had been pastured and manured before the land was plowed. Although the picture was taken after a prolonged drought period, there was not a sign of dry-weather firing. As shown in the close-up view, even the lowest leaves were of a normal green color, and the set of ears gave indication of a very good crop. In the other field, under identical weather conditions, the close-up shows that the corn was fired clear to the tassel. The set of ears was very light. All indications at the time pointed to a complete failure in that field. The difference between the fields was largely one of nitrogen supply, as corn in the second field had followed corn with no manure applied.

Another good illustration of the effect of nitrogen on corn is shown in Figs. 4a and 4b. The pictures were taken on the Ferden rotation

Figs. 4a and 4b. (see color plate section, page 71)

experiment in Saginaw County in 1946. The corn in Fig. 4a followed wheat with no legume in the rotation. The upper leaves were light green, and the lower leaves had turned yellow in the manner characteristic of nitrogen starvation. A tissue test made at the time the picture was taken showed definitely that a shortage of nitrate did exist in the stalks suspected of being deficient.

The corn in Fig. 4b followed alfalfa in the rotation. The color was dark green without a sign of firing, even on the lowest leaves, and the nitrate content of the stalks was found to be very high. Apparently the corn was getting all the nitrogen it needed from that which was added to the soil by the legume bacteria and from the decomposing alfalfa residues. The legume bacteria produce the nodules which may be seen on the roots of leguminous plants such as alfalfa and the clovers. Nodules on an alfalfa plant may be seen in Fig. 5. The bacteria, entering the root from the soil, produce the structure which is known as the nodule. Inside of this the bacteria multiply and perform their task of fixing the atmospheric nitrogen into a form which eventually becomes usable by plants. The nodules do not last for the life of the plant. As they become separated from the plant during its growth, the nitrogen which they contain is turned loose in the soil to be used by other plants or organisms. That is

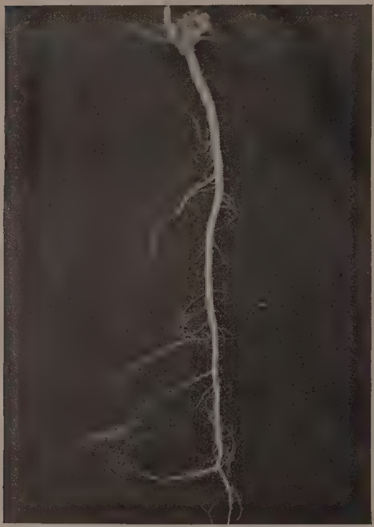

Fig. 5. Legume bacteria multiplying and functioning in the nodules on the roots of leguminous plants change atmospheric nitrogen into forms usable by soil microorganisms and higher plants.

why grasses do so well when they are grown in mixtures with alfalfa or clover.

Oats and Wheat

The symptoms of nitrogen deficiency in oats and wheat are exactly the same as in corn. At first the plants develop a light green color, then the lower leaves turn yellow, the yellowing on each leaf starting at the tip. It is important to remember that the yellowing starts at the *leaf tip*, as that point will be referred to again in differentiating between nitrogen and manganese deficiency. The effect of nitrogen starvation on the appearance of oats is well illustrated by Fig. 6.

Fig. 6. (see color plate section, page 72)

Warm weather came very early in the spring of 1945. After wheat had grown vigorously for several weeks, winter weather returned and temperatures dropped low enough to freeze the ground on several

occasions. By the end of April, wheat had turned so yellow that many farmers considered plowing it under. Some may have done so. The appearance of the wheat plainly indicated nitrogen starvation. Tissue tests and observations made on farms where systems of management varied showed it was actually a lack of nitrogen and not frost which had caused the yellowing. The wheat pictured in Fig. 7 shows that the symptoms were the same as those already de-

Fig. 7. (see color plate section, page 72)

scribed for corn and oats. Some ammonium nitrate fertilizer was applied on a few of the fields most seriously affected, fields where the "frost" damage seemed to be exceptionally bad. The results obtained on one field in Shiawassee County were particularly striking. Within a few days after the nitrate application, the dark green color returned and growth was considerably hastened. On that particular field, the yield increase resulting from the nitrate fertilizer was 7.2 bushels per acre.

Soybeans and White Beans

Even though the soybean is a leguminous plant, it is sometimes found to be suffering from nitrogen starvation. This is often true on poorly drained, heavy soils where the bacteria are not able to function normally because of insufficient air. This condition is probably due as much to the inactivity of the nitrifying bacteria as to the failure of the legume bacteria to perform their task of changing atmospheric nitrogen to combined nitrogen. As soybeans become deficient in nitrogen, the older leaves gradually change in color to a light green and finally to yellow. The change in color is uniform over the entire leaf. In Fig. 8 a nitrogen-deficient leaf is compared with

Fig. 8. (see color plate section, page 72)

one from a normal plant. The nitrogen-deficient leaf came from a poorly drained, Brookston clay loam soil in Lenawee County in 1945.

White beans are not unlike soybeans so far as nitrogen deficiency is concerned. The symptoms are almost identical, a gradual yellowing of the lower leaves and eventually of the entire plant if the deficiency becomes sufficiently serious. It is very common with beans

when the weather is cold and wet during early growth. Such was the case in 1947. On many fields, beans become deficient in nitrogen at about the time they start to set pods. This is especially true on what might be considered the poor bean soils. The green-tissue test for nitrate works very well on beans and soybeans.

Sugar Beets

Sugar beets do their best on soils well supplied with organic matter. This is partly because they require large quantities of nitrogen. From midsummer until the end of the growing season, symptoms of nitrogen deficiency in sugar beets are very common. As the nitrate supply in the soil becomes depleted, the leaves become light green and eventually yellow as the deficiency becomes more serious. The loss of chlorophyl and the resultant yellowing occurs uniformly over the entire leaf. This is an important point, as in the yellowing caused by manganese deficiency, the veins and the leaf tissue close to the veins remain green. This gives the leaf a mottled appearance. Another characteristic of nitrogen starvation is the direction in which the leaves grow out from the crown. Instead of standing erect, as they do in a normal plant, they grow out in a horizontal position to give the beet the appearance of having been stepped on (Fig. 9).

Fig. 9. (see color plate section, page 73)

An examination of Fig. 47 (page 82) furnishes an opportunity to compare the appearance of beet leaves yellowed from three different deficiencies—nitrogen, manganese, and potassium.

The green-tissue test is very useful in checking the supply of nitrogen in a sugar-beet soil. When the crop is growing rapidly, a *soil* test for nitrate is always low, as the plants take it up as fast as it is formed in the soil. Still there might be enough to satisfy the requirements of the plants. In other words, under those conditions, the soil test might not be a true measure of the power of the soil to produce nitrates. A test of the green tissue, however, really shows whether or not the plants, at that particular time, are getting sufficient nitrogen.

Workers at the Michigan station who are interested in soil fertility with respect to sugar-beet production have made it a practice in visiting the sugar-beet-growing areas during the fall months to try to relate nitrogen-deficiency symptoms, tissue tests, and previous

cropping history. In early September it has usually been possible to tell from the color of the plants the number of years that have elapsed since a field has produced alfalfa. Invariably the dark green beets have been found in fields where the last year's crop was alfalfa, or where only one other crop intervened. Tissue tests on such fields have always indicated sufficiently high nitrate levels. Upon finding a field where the beets showed distinct signs of nitrogen starvation, it was usually found upon inquiry that the field had not grown alfalfa or clover for several years. Probably the yellowest field of beets ever observed by the writers was on good Brookston clay loam soil, but where alfalfa, to the knowledge of the farmer, had never been grown

Fig. 10. (see color plate section, page 73)

and where the straw from the grain crop of the preceding year had been plowed under. Apparently the decomposition of the straw had required so much nitrogen that very little was available for the beet plants. The nitrate test made on the leaf petioles did not show a trace of nitrate present. An illustration of how alfalfa affects the appearance of sugar beets may be obtained from Fig. 10.

Tomatoes

As tomatoes become deficient in nitrogen the chlorophyl gradually disappears from the leaves. This action is more rapid in the older leaves but may soon affect the entire plant. The new leaves, however, are always darker in color than are the older leaves. This is because the nitrogen is translocated from the old to the new leaves when the supply in the soil is inadequate for the needs of the plant.

As the chlorophyl fades and the leaves become gradually lighter green to yellow, the veins become purple in color. Where the deficiency becomes very severe the older leaves become entirely yellow and the purple color becomes very pronounced even to the very smallest veins. The network of the veins after the purple color develops is visible from both sides of the leaf but is more pronounced on the lower side. The purple color extends also to the petiole of the leaf and is somewhat noticeable on the main stem of the plant.

One should be careful to avoid confusion between the purple color of petioles and veins caused by nitrogen deficiency and the purple of the under side of the leaves caused by phosphorus deficiency. In the latter case the entire under surface, including the veins, becomes

purple. The appearance of such leaves may be compared by referring to Fig. 21 (page 76).

Cucumbers

When cucumbers are deficient in nitrogen, the oldest leaves lose their chlorophyl first. The yellowing then progresses from leaf to leaf toward the growing tip. It is important to remember that the yellowing is uniform over the entire area of each leaf. The veins do not remain green. The plants shown in Fig. 11 illustrate this very nicely.

Fig. 11. (see color plate section, page 73)

Cineraria

Potted plants require large quantities of nitrogen. When the element becomes deficient, the lower leaves gradually turn yellow over their entire area. The yellowing is not confined to leaf edges as is true where the starvation is for potassium. The contrast is shown in Fig. 38 (page 76). The yellowing gradually works up the plant until finally the entire plant has become very light green to yellow.

Coleus

The coleus plant, grown for its beautiful foliage, may be varied in color by regulating the supply of nitrogen. The plants shown in Fig. 12 were grown in an experiment to determine the effect of vari-

Fig. 12. (see color plate section, page 74)

ous organic materials on growth and appearance. Those two particular pots were among four which were filled with Miami silt loam soil in which had been incorporated a large quantity of chopped straw. The plants made less growth than did those grown on soil containing manure, and their color was a much brighter red. Green-tissue tests showed the bright red plants to be devoid of nitrate nitrogen. Apparently the bacteria had used so much nitrogen in decomposing the straw that little was left available to the coleus.

At the termination of the experiment, two of the four nitrogen-starved plants were supplied with soluble nitrogen in the form of ammonium nitrate. Their color soon became a very deep red. The contrast between the two colors is shown in Fig. 12. Tissue tests at that time showed the deep red plant to be very high in nitrate nitrogen. The tests were made on leaf petioles.

Grasses

Like their close relatives, corn, oats, and wheat, the common grasses require large quantities of nitrogen. Most persons have had occasion to witness the quick change in color which results from the application of soluble nitrogen fertilizers on lawn and pasture grasses. A close examination of nitrogen-deficient blue grass, timothy, sudan grass, or smooth brome grass shows the symptoms to be exactly the same as those described for oats and wheat, a general light green color with yellowing starting at the tips of the lowest leaves. Brome grass responds very quickly to applications of soluble nitrogen. This is why it does so well when grown in a mixture with alfalfa. Timothy is very responsive to soluble nitrogen fertilizer. The effect of 10-10-5 fertilizer on timothy yields on the Johnson farm near Iron River is shown by comparing Figs. 13a and 13b. The effect which nitrogen

Fig. 13a.

Timothy hay from an unfertilized plot. Compare with Fig. 13b.

Fig. 13b.

Timothy hay from an equal-sized plot which received 10-10-5 fertilizer. Compare with 13a.

has on the color of pasture grasses was well illustrated (Fig. 14) in a pasture field on the Kellogg farm near Battle Creek in 1945. The grass was very yellow except on the spots where urine had been voided by the animals, where it was much larger and very dark green.

Fig. 14. (see color plate section, page 74)

Fruit

It has been common knowledge for years that fruit trees must be well supplied with nitrogen. Where there is a deficiency, apples make a small set of fruit and leaves mature while yet small. There is a gradual loss of chlorophyl, noticeable first on the oldest leaves on the current year's growth. An increase in development of anthocyanin pigment may be associated with nitrogen deficiency. Twig and spur elongation stops early and the twigs are stiff and woody.

Peaches are especially sensitive to a deficiency of nitrogen. As with apple trees, there is a gradual loss of chlorophyl, first apparent on the oldest leaves of the current year's growth. Red spots appear on the leaves. Nitrogen-deficient and normal leaves are shown in Fig. 15. During the early part of the season, symptoms may be corrected by an application of soluble nitrogen. They may be prevented by applying adequate amounts of nitrogen before growth starts in the spring.

Fig. 15. (see color plate section, page 74)

NITROGEN SURPLUSES

After all this discussion about nitrogen deficiency, it seems unwise to leave the subject without mentioning the fact that nitrogen excesses may be harmful and that for many crops it would not be desirable to maintain a continuously high level of available soil nitrogen (nitrate) throughout the season. This is especially true of fruit. If nitrate levels are too high, too much new vegetative growth is likely to occur with too little flower-bud differentiation. The accumulation and storage of carbohydrates may be inhibited. If this condition continues until late in the season, much winter killing may result.

A continuously high nitrate level in the soil tends to delay flowering and fruiting. For this reason, it is desirable in the production of certain flowering plants to maintain the level high during the period of rapid vegetative growth, then withhold or remove soluble nitrogen to induce flowering.

A very late application of soluble nitrogen for such crops as tomatoes, potatoes, or sweet corn may stimulate vegetative growth and delay fruiting or tuber formation to the extent of actual injury to the crop. In other words, nitrogen deficiency at certain times is actually desirable.

PHOSPHORUS DEFICIENCY

In the raw materials from which soils have been formed, phosphorus existed as a component of the mineral "apatite." As a result of the weathering processes which have changed soil materials into soil, much of the apatite has been broken down. The released phosphorus has combined with other elements to form secondary minerals and complex chemical compounds. Since the quantity of apatite in the soil-forming rocks was generally low, it follows that the resulting soils are low in phosphorus.

During the years of soil formation, a portion of the released phosphorus was taken up by the plants and returned to the soil as a part of the organic matter. This means that at the present time soils high in organic matter contain more phosphorus readily available to plants than do soils low in organic matter. It is true, of course, that the organic matter must be in a state of decomposition for the phosphorus to be available to growing plants.

With the release of phosphorus in the soil, either from the primary and secondary minerals, from the decomposition of organic matter, or from other sources, some is absorbed by the clay particles. In fact this absorption is so great that very little phosphorus is lost from a soil by leaching. This phenomenon is further responsible for the immobility of phosphorus ions in a soil. This immobility means that plant roots must move to the phosphorus, as the movement of the phosphorus toward the roots is very slow. The phosphorus absorbed by the clay is probably removed from the clay particle only by direct contact with the plant root.

Another source of phosphorus in the soil is that which is often termed the "difficulty available phosphorus." This is in the form of

iron and aluminum phosphate compounds, so slowly available that profitable crops cannot be produced if other sources are not available. It is desirable to raise the pH of soils above 6.8 to discourage the formation of these difficultly available phosphorus compounds.

"Easily available phosphorus" exists in the soil in the water-soluble form and as calcium and magnesium phosphates. The quantity existing in water-soluble form at any one time is indeed very small, from none in less fertile soils to perhaps 40 pounds per acre in very fertile soils. A considerable quantity may exist as calcium and magnesium phosphates, provided the pH of the soil is above 6.8. Below this pH these phosphates are unstable.

Soluble phosphorus combines readily with various compounds in the soil. In commercial fertilizer the phosphorus is usually in the form of calcium phosphate. If the pH of the soil is above 6.8, the calcium phosphate remains stable and the phosphate ion is thus held in union with the calcium, a form in which it is readily available to plants. It is true, however, that if the pH is too high (probably above 7.5) phosphorus intake by plants may be slow. In other words, very high alkalinity may be just as harmful as strong acidity. If the pH of the soil is below 6.8, calcium phosphates break down and the phosphorus combines with hydrated iron oxides to form iron phosphates that are not easily available. Combinations with aluminum may also take place. Under such conditions, phosphorus starvation may exist even though phosphate fertilizers have recently been applied.

Phosphorus starvation is usually most pronounced during the early growth of plants. This is especially true if growing conditions during that time are not ideal. Corn, for instance, during a cold, wet spell early in the season, may show marked signs of phosphorus deficiency, even on soil which tests rather high in available phosphorus. This is because at that time, owing to the slow growth, the roots are not extending to the phosphorus and, because of its immobile condition in the soil, the phosphorus is not moving to the roots. Furthermore, during periods when growth is almost completely at a standstill, new root hairs are not being formed. It is through the new root hairs that nutrients are taken into the roots. When weather conditions improve, growth increases and the phosphorus deficiency symptoms often disappear. Even though the specific symptoms disappear, however, the plants may have been stunted and final yields depressed.

Phosphorus is essential for cell division. When a shortage exists, new growth is depressed and plants become stunted. Since there is an attempt on the part of the plant to furnish phosphorus for new growth, the element is transferred from old to new tissue. For this reason it is desirable to make tissue tests for phosphorus on both the old and newer growth. For instance, the new center leaves of sugar beets may be high in phosphorus when the older outside leaves are low. This shows that phosphorus has been transferred from the older leaves to the central growing tissue. At such a time the plant may not yet have suffered from phosphorus starvation, but the time is rapidly approaching when the deficiency will slow up growth. The outer leaves may become so depleted in phosphorus that death results. Whenever sugar beets are found to have a lot of dead leaves around the outer edges, it is a sure sign of some nutrient deficiency, unless, of course, some disease is responsible.

Small grains may fail to tiller when phosphorus is lacking, and an excess tends to induce sucker formation in corn. Phosphorus is said to stimulate root production and to increase resistance to disease. This is probably due to a stimulation of cell division and a more vigorous metabolism. It has been shown that black root of sugar beets causes much less damage on plots heavily fertilized with phosphorus than on unfertilized plots.

Phosphorus is essential in seed formation. With all conditions normal, a plant stores up phosphorus to be moved toward the fruiting region as the seeds begin to develop. If the supply of phosphorus during the vegetative stage of growth has been only sufficient to keep the plants alive, there will be no reserve supply for this extra demand at fruiting time. Such a condition results in yellowing and dropping of older leaves while seeds are forming.

Corn

In young corn plants starved for phosphorus, nitrogen is usually high. This gives the plant an unusually dark green color. Phosphorus-starved plants also accumulate sugars. When the sugar concentration becomes abnormally high, anthocyanin pigment accumulates, which turns the leaves to a reddish purple. This usually happens during the early growth of the plant and is most pronounced during periods of adverse weather when growth processes are slow. The reddening starts at the tip of the leaf and proceeds along the edges

toward the stalk. A badly deficient plant is shown in Fig. 16. A close-up view of an individual leaf is shown in Fig. 1a (page 69).

Fig. 16. (see color plate section, page 75)

As the plants become older and root development increases, the reddening usually disappears and no definite symptom of phosphorus deficiency remains except that the plant may have been stunted in growth. As seed time approaches, such plants will turn yellow, provided the starvation for phosphorus has remained serious. The yellowing will start on older leaves in much the same manner as does nitrogen deficiency. Confusion between the two may be avoided by use of tissue tests. In some cases symptoms of phosphorus deficiency appear in young corn plants on soils which are rather well supplied with phosphorus. This happens during periods when growth is restricted because of cold wet weather. If such a condition is suspected, it should be verified by making soil tests for phosphorus.

Grains

The small grains are very responsive to phosphorus fertilizers, especially during early growth, but deficiencies cannot be readily detected by any definite leaf symptoms. When phosphorus is lacking in the soil, the plants start slowly and do not tiller well. Some reddening similar to that of corn is sometimes evident. In cases of extreme deficiency and when the season is cold and wet during early growth, there is a general yellowing of the leaves which may be confused with nitrogen deficiency. It is easy to avoid such confusion, however, by making green-tissue tests for phosphorus and nitrate on the stalks of the young plants.

Alfalfa

Alfalfa is very responsive to phosphate fertilizer, especially on heavy soils. When the available supply in the soil is inadequate, the plants start slowly and remain small. At blossom stage the lower leaves turn yellow and drop off. Lack of leaves results in poor quality hay.

If phosphorus deficiency is suspected because of slow growth, and symptoms of potassium deficiency are absent, a test for phosphorus is usually sufficient to confirm the suspicion. The effect of phosphate in stimulating the early growth of alfalfa was demon-

strated in a striking way on a Miami loam soil on the Dilman farm near Cass City. The effect of the fertilizer is shown in Fig. 17.

Fig. 17. (see color plate section, page 75)

Sugar Beets

A deficiency of phosphorus delays the emergence of sugar beet seedlings and makes them more subject to disease. Once the plants have emerged they grow slowly and become stunted. The stunted plants have small, dark green leaves which, in extreme cases, are fringed with red, as shown in Fig. 18. If the red color is present, the

Fig. 18. (see color plate section, page 76)

symptom is very reliable. If the red fringe is not in evidence, it is well to make a tissue test for phosphorus. A low-phosphorus test, of course, confirms the suspicion. Such leaves always test high in nitrate. The test should be made on the petioles of the older leaves.

The unusually dark green leaves are the result of an extremely high nitrate content. When growth is held back because of a lack of phosphorus, the plant takes in nitrate in excess (luxury consumption). The small green leaves on phosphorus-deficient plants stand more erect than on normal plants. This is in contrast to the horizontal position of the light green leaves on the nitrogen-deficient plant shown in Fig. 9 (page 69).

After about the middle of the growing season, if phosphorus deficiency continues to be serious, the beet leaves gradually lose their dark green color and finally become very light green or yellow as shown in Fig. 19. The older leaves die, and the condition very closely

Fig. 19. (see color plate section, page 76)

resembles nitrogen deficiency. Such plants will, however, have a high content of nitrate, so the tissue test is very useful in avoiding a mistake. During the latter part of the growing season it is always desirable to use the nitrate test to distinguish between these two deficiencies.

Beans

Generally beans do not exhibit definite symptoms of phosphorus deficiency except that growth may be slow. The result is a stunting

of the plants and a depression in yield. Beans are a short-season crop. Accordingly growth must be rapid if maximum yields are to be attained. That is why fertilizers for beans need to be close to the seed. The fertilizer should not touch the seed, however, as poor germination may result.

In cases of extreme phosphorus starvation, bean leaves turn yellow and die. This occurs first on the older leaves, as illustrated in Fig. 20.

Fig. 20. (see color plate section, page 76)

It apparently is the result of rather complete transfer of the phosphorus from the older leaves to the growing tissue. Since the symptom is less common than is the yellowing of bean leaves from deficiencies of nitrogen, potassium and manganese, care must be taken to avoid confusion. Perhaps the safest precaution is the green-tissue test and the soil reaction test. If the yellowing is really due to a lack of phosphorus, the affected leaf petioles will test low in phosphorus and high in nitrate and potassium. There is a possibility of eliminating manganese deficiency as a contributing factor by determining soil reaction. If the pH is below 6.8 there is little possibility of a shortage of manganese. Furthermore, yellowing due to a shortage of manganese does not start on the lower leaves but appears throughout the plant, and it is uniform over the entire area of each leaf.

Tomatoes

The growth of tomatoes is seriously affected by a deficiency of phosphorus. Especially is this true if the shortage occurs during early growth. Young seedlings become very dark green and the lower sides of the leaves, including the veins, turn purple. This need not be confused with nitrogen deficiency symptoms because in the latter only the veins and petioles become purple with the leaf tissue between the veins showing very light green or yellow. A comparison is shown in Fig. 21. The dark green color is a result of the intake of

Fig. 21. (see color plate section, page 76)

an excess of nitrogen while plant growth is held back by the phosphorus shortage.

After root systems become well established, tomatoes, like corn, sometimes are able to obtain sufficient phosphorus to eliminate the characteristic purple discoloration. For that reason the symptom is not so common on older plants. In the case of nitrogen deficiency

the purple color of the veins remains as long as the deficiency persists, even until the death of the plant.

On strongly alkaline soils or on soils high in calcium, as occurs in some greenhouse soils watered with hard water, phosphorus deficiency symptoms are common. Apparently the high alkalinity lessens the intake of phosphorus by the plant.

The green-tissue test for phosphorus works well on tomatoes. Blank or low tests mean that phosphate fertilizer should be applied at once. Tests remain low even after the purple color disappears. Apparently the purple shows up only when the deficiency is very severe.

POTASSIUM DEFICIENCY

Potassium occurs in the soil largely in the mineral form. During the processes of weathering, the minerals are reduced to clay with the liberation of potassium in carbonate form. As potassium carbonate is easily soluble, the potassium ion is free to unite with secondary compounds to form insoluble silicates, or it may be removed by growing plants, or it may become attached to the clay colloids. In this latter role the ion has given up its positive charge and is called an exchangeable ion. As weathering is constantly going on, some potassium is always in solution and is in danger of being lost in drainage water. From the average soil under rotation farming, there is probably as much potassium lost in drainage water as is removed by crops.

An acre of soil down to plow depth may contain as much as 40,000 pounds of potassium. One must not be deceived, however, into thinking such a quantity may be sufficient for maximum yields for a long time, because most of it is in the form of unweathered minerals, made available to plants only through the slow processes of weathering.

The potassium required by plants must come largely from that which is absorbed by the clay. Fine clay, of colloidal dimensions, carrying a negative electrical charge attracts to it positively charged ions such as potassium. Such ions, held against loss by leaching, are readily removed from the soil particle upon contact by the plant root. The potassium thus removed from the clay is gradually replaced by that which is released during the weathering of minerals. As this replacement is slow, there may develop, during a vigorous cropping program, a serious depletion of the exchangeable potassium.

Eventually the time comes when the crop cannot obtain enough for maximum growth.

Potassium is released from decomposing organic matter. In soils well-supplied with organic material, a considerable portion of the potassium used by plants comes from this source. Cover crops take up potassium which might otherwise be lost by leaching and return it to the soil. Through decomposition, it is quickly released again for use by growing plants.

A small quantity of soluble potassium exists in soil. In clay soils, the affinity between clay and potassium ions is so high that a water extract of the soil may be almost devoid of potassium. However, enough might be available from the organic matter and the clay to grow a crop. On the other hand, a sandy soil might contain a considerable quantity of soluble potassium but so little in the exchangeable form that crops would soon show symptoms of starvation.

Symptoms of potassium deficiency are common on sandy soils because of the scarcity of potassium-bearing minerals and the low content of clay. They are also common on muck soils, formed largely from organic materials low in potassium. In strongly alkaline soils the intake of potassium is apparently inhibited by the high concentration of calcium. On such soils, symptoms of potassium deficiency are more common than they are on neutral and slightly acid soils.

The role of potassium in plants is not known, but experiments have shown that it is essential. That most of the potassium remains soluble in the plant is shown by the fact that it may be removed from dried plant tissue by leaching with water. There is some evidence that potassium sometimes moves from maturing plants back into the soil. Young tissues contain more potassium than do older tissues. This shows the element to be essential for growth. As the supply from the soil becomes inadequate, potassium moves out of the older leaves into the growing tissue. It apparently leaves the edges of the leaves first, as yellowing starts at the tips and edges. By the time the yellowing has reached the central area and base of the leaf, the edges have usually turned brown and may have broken off. As the deficiency becomes more severe, the potassium moves out of the next older leaves and so on until even the newest leaves sometimes show signs of potassium starvation. Under certain conditions, green veins are prominent on potassium-starved leaves. In such cases the leaf yellowing *is not uniform.* This makes it possible to avoid confusion with symptoms of manganese, calcium, or iron

deficiencies. Note the potassium-starved bean shown in Fig. 28.

A word of caution seems desirable at this point. Certain virus diseases may produce similar symptoms. In some crops, the ravages of insects, such as leaf hoppers, may produce an appearance similar to that resulting from a deficiency of potassium. This is true of alfalfa, and the condition has been reported for apples. It is possible to confirm or disprove the suspicion of potassium deficiency by the green-tissue test.

Corn

Symptoms of potassium deficiency may occur in corn at any time during the growing season. The condition is most common, however, after the corn has made several weeks' growth. The pattern of yellowing is different from that of nitrogen deficiency, as shown by Fig. 1a. The yellowing starts at the tip of the leaf and proceeds along the edges toward the stalk, instead of along the midrib. The edges soon turn brown and become dry, which has led to the term "leaf scorch." The rustling caused by the wind soon frays the edges and gives them the ragged appearance so common when the deficiency becomes serious.

As is the case with nitrogen deficiency, potassium deficiency is apparent first on the lowest leaves. When the oldest leaves are entirely yellow, the newest leaves may be normal. This is shown by Fig. 1b.

Fig. 1b. (see color plate section, page 69)

When the pattern of yellowing is indefinite, conclusions may be verified by the use of tissue tests. If the yellowing is really due to potassium deficiency, high nitrate and phosphorus tests will be obtained, and the potassium test will, of course, be low, usually almost blank.

Small Grains

With small grains, if symptoms alone are relied upon, there is danger of confusion between potassium and nitrogen deficiency. This may easily be understood by studying the potassium-deficient barley leaves shown in Fig. 22. The plants were taken from unfer-

Fig. 22. (see color plate section, page 77)

tilized plots on Hillsdale sandy loam soil. The lower leaf of each plant had turned yellow from the tip about half the length of the leaf. There was a distinct tendency for the yellowing to proceed

Fig. 23a. Barley grown on Miami loam soil, with and without potash in the fertilizer.
Left—3—12—0 Right—3—12—12

faster along the edges of the leaves than in the middle, exactly as potassium deficiency develops in corn. With the grains, however, the leaves are so small that this characteristic is likely to be unnoticed.

When potassium deficiency is suspected in the grains, it should be confirmed or disproved by tissue tests. With the grains the tests are very clear and dependable. The results of the potassium test are shown in Fig. 22. The unfertilized, deficient plants contained barely a trace of potassium, while the normal plants from fertilized plots tested high.

Barley seems to require higher levels of potassium than do wheat and oats, and it sometimes exhibits a specific symptom of potassium

starvation. It was illustrated very strikingly in greenhouse experiment. Barley was grown on Miami loam soil without potash and with potash in the fertilizer. The difference in growth as a result of the potash in the fertilizer is shown in Fig. 23a. Besides the difference in size of the plants there was a difference in the appearance. In all four of the pots which did not receive potash, the leaves were covered with small dark blotches which persisted even until maturity, as shown in Fig. 23b. There were none of these blotches on the plants which received potash fertilizer. The blotches were examined by a pathologist and found to be free of organisms. When field-grown barley displaying this symptom is thought to be deficient in potassium, one should confirm the suspicion by the green-tissue test for potassium.

Alfalfa and Clover

Leguminous crops as a whole require rather high levels of available potassium. As the supply in the soil becomes exhausted, the older leaflets start to turn yellow at the tips and along the edges. At the same time white dots appear in the yellowed region or along the boundary between the yellow and green areas, as shown by Figs. 24 and 25. The alfalfa leaf shown in Fig. 24 was grown in the greenhouse on Plainfield sand deficient in available potassium. In those

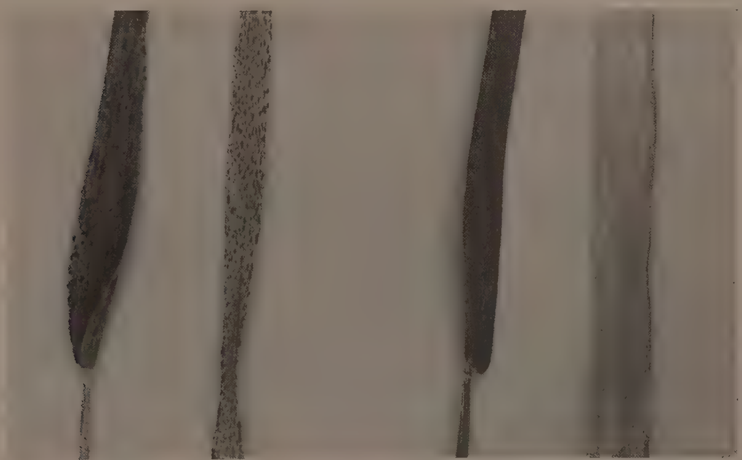

Fig. 23b. Barley leaves grown in the pots shown in Fig. 23a. The dark colored blotches indicate potassium deficiency. The blotches persist even until maturity.

Fig. 24. Alfalfa leaf grown in the greenhouse on Plainfield sand. The yellow edges on the leaflets and the white dots arranged in this pattern are sure symptoms of potassium deficiency.

pots which had been fertilized with potash, the alfalfa leaflets did not turn yellow and did not contain the white dots. The plant shown in Fig. 25 was grown in the field on Warsaw loam where soil tests verified the fact that potassium was definitely a limiting factor.

Fig. 25. An alfalfa plant grown in the field on Warsaw loam, shown by soil tests to be lacking in available potassium. The green plant tissue also tested exceedingly low in potassium. Note that in this plant the white dots were distributed throughout the yellowed parts of the leaflets.

In the spring of 1946, phosphate and potash fertilizers were applied separately and together as top-dressings on a large number of alfalfa and clover fields. On many of the fields, the increases in yield as a result of the fertilizers were very marked. On many of the heavier soils, the greater response came from phosphate with no response from potash in the absence of phosphate. In several instances, symptoms of potassium deficiency were very marked at harvest time on *only* the phosphate-treated plot. Apparently there was potassium enough in the soil to supply the limited growth on the unfertilized soil, but where phosphate fertilizer was applied the increased growth soon exhausted the supply available in the soil and the plants showed symptoms of deficiency.

The lack of response to potash without phosphate strengthens this conclusion. On all fields where these observations were made, tissue tests showed the potassium content of plants on the phosphate-treated plots to be lower than it was in plants from the untreated plots, and of course very much lower than in plants from potash-treated plots. In all cases the plants from the phosphate-treated plots were high in phosphate at harvest time. The leaves of alfalfa and clover shown in Fig. 26 were taken from the phosphate-treated

Fig. 26. (see color plate section, page 77)

plot on Napanee silt loam soil on the Davis farm near Sandusky. The yield was increased by the superphosphate fertilizer from 1.58 to 2.58 tons per acre. The symptoms of potassium deficiency occurred only on the phosphate-treated plot. Results of the tissue test are shown in Fig. 27.

Fig. 27. (see color plate section, page 77)

As already suggested, one must be careful not to confuse injury to alfalfa by leaf hoppers with potassium deficiency. When leaf-hopper injury is serious, as it often is during the second growth, the leaflets turn yellow at the tips and along the edges in the manner so characteristic of potassium deficiency, but *the white dots are not present.* Another very good way to differentiate between leaf-hopper injury and potassium deficiency is to make a green-tissue test for potassium. If the injury is actually due to leaf hoppers, the potassium test will be even higher than normal. This is because, as the leaf hoppers

restrict the growth of the plant, potassium tends to accumulate as it does when growth is restricted by a lack of some other plant nutrient.

Beans, Soybeans, and Cowpeas

These plants are very similar so far as symptoms of nutrient deficiency are concerned. Symptoms of potassium deficiency usually appear while the plants are still in the early stages of growth. The symptoms first appear on the older leaves and work gradually toward the newer growth. The newest leaves are usually normal in appearance. As is invariably true with potassium deficiency, the yellowing appears first at the tip and edges of the leaflet and gradually spreads toward the center and base. As time goes on, the tissue along the edges becomes necrotic (brown and dry). Eventually the entire leaf dies. Apparently as the leaflet edges become yellow, growth becomes slower in the yellow areas and continues at a more normal rate in the remaining green portions. The result is a decidedly crinkled appearance as shown in the potassium-deficient leaf pictured in Fig. 28. In contrast, a normal leaf appears to have been

Fig. 28. (see color plate section, page 78)

pressed and is uniformally green in color. Note the contrast between the leaf badly deficient in potassium and the one deficient in manganese. Both leaves are yellow, but the patterns are decidedly different.

During cold, wet periods in the early part of the growing season and during unusually dry periods in midsummer, potassium-deficiency symptoms are very common in white field beans and soybeans. On the experimental plots shown in Fig. 29, white beans had

Fig. 29. (see color plate section, page 78)

followed soybeans. The beans on all plots which had not received potash fertilizer were decidedly yellow. In fact, only the very newest leaves were normal in color when the picture was taken. The plots which had received only phosphate fertilizer contained plants even more yellow than did the unfertilized plots.

In several instances, white beans as badly deficient as those shown in Fig. 29 have been profitably side-dressed with potash fertilizer. It is better, of course, to avoid the occurrence of such a condition by applying the proper fertilizer at the time of planting.

Soybeans, like white field beans, are quick to show symptoms of potassium deficiency. The pattern of yellowing is exactly the same, except that perhaps the contrast between the yellow edges and the green central and base portions of the leaflet is even more striking on soybeans than on white beans. A soybean leaf deficient in potassium is shown in Fig. 30. As with white beans, the question always

Fig. 30. (see color plate section, page 78)

arises as to whether anything can be done about it after the symptoms appear. An application of potash fertilizer, applied as a side-dressing as soon as the symptoms appear may have a considerable effect on yields. Such a side-dressing was made on Hillsdale sandy loam in Eaton County on August 2, several weeks after the symptoms of deficiency had first appeared. On September 5, the treated rows, viewed from a distance, had regained their normal color and had gained markedly in growth over the untreated rows. The new growth on the treated rows had retained its normal green color and the plants had made a much more vigorous growth. The bundles shown in Fig. 31 illustrate the difference in growth which had oc-

Fig. 31. Soybean bundles, each from 1 rod of row. The left bundle was taken from an untreated row. The right bundle was taken from the row directly adjoining which had been side-dressed on August 2, with muriate of potash at the rate of 100 pounds per acre. The harvest was made on September 5.

curred during the 34 days after the potash treatment was made. Had the fertilizer been applied earlier, the difference in vegetative growth would probably have been even greater.

Cowpeas growing on a soil deficient in available potassium develop deficiency symptoms not unlike those described for soybeans and white beans. In Fig. 32 a deficient leaf is compared with a normal leaf.

Fig. 32. (see color plate section, page 79)

Green-tissue tests may be made to good advantage on beans, soybeans, and cowpeas. When potassium deficiency becomes so serious that symptoms develop, the petioles of deficient leaves always test low. Usually the test is blank. At the same time, the new green leaves may give a rather high test. This is because the potassium from the old leaves is being translocated to the new leaves.

Potatoes and Tomatoes

Potatoes require large quantities of potassium. The crop is commonly grown on muck and sandy soils where the supply of available potassium is rather limited. As a result, recommendations for potato fertilizers include those high in potash. In Fig. 33 are shown two potato leaves grown in greenhouse pots. The yellow ragged leaf is typical of those found on plants deficient in potassium.

Fig. 33. (see color plate section, page 79

Tomatoes, like potatoes, require plenty of potassium. Fig. 34a shows how markedly the addition of potash to the fertilizer increased the growth of tomatoes on a good Miami loam soil. On the plant which had not received potash, most of the leaves were yellow when the picture was taken. When the element is deficient during the early stages of growth it first shows up as a yellowing of the tips and edges of the oldest leaflets. The deficiency shows up earlier in the stage of growth when soil nitrogen and phosphorus levels are high and when nitrogen levels are high the yellowing is commonly accompanied by the formation of white dots in a manner already described on alfalfa and clover. This is illustrated in Fig. 34b.

As the season progresses potassium deficiency symptoms on tomatoes do not disappear as do those of phosphorus deficiency, but they change somewhat in appearance and become more pronounced as the plants produce fruit. On the older plants the symptoms of

Fig. 34a. Tomato plants without and with potash on Miami loam soil. Most of the leaves on the left plant, which had not received potash, were showing signs of potassium deficiency at the time the picture was taken. Leaves deficient in potassium are shown in Figs. 34b and 34c.

deficiency on the newer leaves are much as described for the old leaves of the young plants but the old leaves of the old plants (those old enough to bear fruit) present a considerably different appearance. The yellowing occurs as a mottling with the area between the main

Fig. 34b. (see color plate section, page 79)

veins much more yellow than the area directly adjacent to the veins. The mottling starts near the leaflet edges and progresses inwardly until it includes almost the entire area, as illustrated in Fig. 34c.

Fig. 34c. A mature tomato leaf deficient in potassium.

On potassium-deficient plants, the newest leaves are of a much darker green color than they are on those severely deficient in nitrogen. In fact, some of the older leaves remain dark green so the general appearance is that of a contrasting dark green and yellow as compared with a very light green and yellow on nitrogen-deficient plants.

Sugar Beets

Sugar beets contain a considerable quantity of potassium. Therefore, it is not surprising that a deficiency is very soon reflected in the appearance of the plant. The oldest leaves are affected first. They

start turning yellow first at the tip and along the edges. Gradually the yellow area works toward the center of the leaf and the edge turns brown. Sometimes the chlorotic area becomes yellowish gray rather than a distinct yellow as is characteristic of bean leaves yellowed by potassium starvation. The Number 2 leaf shown in Fig. 47 (page 78) was taken from a potassium-deficient sugar beet.

For comparison, leaves from beets starved for nitrogen and manganese are shown in the same picture.

Tissue tests for potassium should be made on the leaf petioles. It has sometimes been observed that plants showing slight to medium symptoms of potassium starvation test low to medium in potassium. In other words, plants with such symptoms do not always test blank. This probably means that for maximum growth, the petioles of sugar-beet leaves should contain potassium sufficient for a high test.

Cucumbers

In Fig. 11 are shown cucumber plants which were starving for nitrogen. The characteristic symptom is a gradual fading of the chlorophyl over the entire leaf. Now contrast such an appearance with that of the leaf shown in Fig. 35, where the yellowing was

Fig. 35. (see color plate section, page 79)

distinctly around the leaf edges. In cucumber plants suffering from potassium starvation, the portion of the leaf blade nearest the petiole remains green long after the tip and sides of the blade have turned yellow and died.

Green-tissue tests work very well on cucumbers. In greenhouse pot tests, it is always easy to differentiate between treated and untreated pots, with reference to any one of the three elements, nitrogen, phosphorus, or potassium, by such tests.

Cabbage and Celery Cabbage

These two plants are quick to show symptoms of potassium starvation. In Figs. 36 and 37, leaves from deficient plants are compared with normal leaves. The oldest outside leaves are affected first. The newest center leaves may be perfectly normal on plants very severely starved for potassium.

Figs. 36 and 37. (see color plate section, page 80)

Cineraria

Florists are finding that it is essential to maintain nutrients at the correct levels if plants carrying green healthy foliage are to be produced. This is especially true of cineraria. A plant having the most beautiful blossoms will be classed as second rate if the leaves are off-color. When the level of available soil potassium is low, the older leaves of the cineraria turn yellow around the edges. Soon the edges become brown, and portions drop away, giving the leaf a ragged appearance. In Fig. 38 a plant which had received very little potash but plenty of nitrogen is shown in comparison with a normal plant and one which received plenty of potash but very little nitrogen.*

Fig. 38. (see color plate section, page 80)

The picture shows, as is usually the case, that a deficiency of either nitrogen or potassium causes delay in flowering. Likewise, of course, an *excess* of either element will delay flowering. Deficiencies in cineraria are readily detected by the green-tissue test.

Stocks

Stocks grown in soil low in available potassium tested very low in potassium, and very early in their stage of growth showed symptoms of deficiency. The lower leaves first turned yellow at the tips. The yellowing progressed rapidly toward the base of the leaf and worked from leaf to leaf up the plant. The very newest leaves, however, were always normal in color. An extremely deficient plant is shown in Fig. 39.

Fig. 39. (see color plate section, page 81)

Tests showed the yellowed outer leaves to be devoid of soluble potassium, while the very newest green leaves contained enough to give a positive test. Potassium, of course, was being moved from the old to the new leaves. One may assume, perhaps, that in such a plant the same potassium is used several times.

Geranium

This plant seems to be very sensitive to a lack of available soil potassium. When the element is extremely deficient, the leaves develop like those shown in Fig. 40. Tissue tests work very well on

*From an experiment conducted by John Gartner, graduate student in floriculture, Michigan State College.

geraniums, and when potassium deficiency is suspected it is well to perform a test to confirm the symptom. Use the petioles of the leaves.

Fig. 40. (see color plate section, page 81)

MANGANESE DEFICIENCY

Manganese occurs in soils in several forms — as exchangeable manganese, as a cation attached to the clay, as a part of organic matter, and as a constituent of certain minerals, chief of which are pyrolusite ($Mn\,O_2$), rhodonite ($Mn\,Si\,O_3$), and rhodochrosite ($Mn\,CO_3$).

To be available to plants, manganese must exist as exchangeable manganese, as a part of organic matter, or as inorganic, easily reducible manganese. Manganese is readily oxidized to the manganic form. Under certain conditions manganic manganese may be reduced to the manganous form. This manganous-manganic equilibrium has been discussed fully by Sherman and Harmer* and by Fujimoto and Sherman.** Briefly, it is affected by relative acidity or alkalinity, content of lime and phosphate, aeration, temperature, clay content, moisture, and the presence of certain reducing and oxidizing compounds. On alkaline soils, high in lime, the equilibrium would swing toward the manganic side, and plants would be unable to obtain sufficient manganese for normal growth. Likewise any manganese applied in a soluble form, such as manganese sulfate, would quickly be oxidized to the manganic form.

Acid conditions favor the formation of manganous manganese. Since this form of manganese is readily available to plants, one would not expect to encounter manganese deficiency on acid soils. Such seems to be the case. It is believed that pH 6.5 to 6.8 marks the border line for manganese deficiency on mineral soils in Michigan.

Manganese is rather easily leached from acid soils. For that reason the total levels may become rather low. When such soils are limed above pH 6.5, it is more likely that plants grown on them may suffer from lack of manganese than would be the case for soils with a normal pH above 6.5.

Since manganese deficiency usually occurs on alkaline soils, it seems logical that the reaction of the soil should be determined first when it is necessary to make tests to confirm some suspected deficiency.

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*Soil Science Society of America Proceedings, 7: 398–405, 1942.

**Soil Science Society of America Proceedings, 10:107–112, 1945.

The role of manganese in the plant is not clearly understood. McHargue* has suggested that manganese performs some function in photosynthesis. Others contend that it increases the activity of oxidizing enzymes in plants. Some look upon it as a regulator of the intake and state of oxidation of certain other elements in the plant, especially iron. There is considerable evidence, for instance, that manganese must be present in the plant to keep iron in an oxidized state so it will not become toxic in the plant. In other words, manganese deficiency may actually be iron toxicity. There is need for more research along this line.

Symptoms of manganese deficiency first appear in relatively young but not always the youngest growth. When the symptoms start early, in very young plants, practically all leaves may be affected, but when the symptoms first appear after a plant has reached a considerable size, the older leaves may remain green while the upper portion of the plant becomes chlorotic. This shows that the element is not readily translocated from old to new tissue, so a constant supply is necessary for normal growth.

On most plants, manganese-deficient leaves are distinctly mottled. The leaf tissue between the veins becomes increasingly lighter green until it is definitely yellow, but the veins remain green. The color pattern is uniform over each individual leaf. By the green veins, it is rather easy to differentiate between chlorosis due to manganese deficiency and that caused by a lack of nitrogen. With some plants, the leaf tissue directly adjacent to the veins may also remain green.

Care must always be exercised to avoid confusion between the symptoms of certain virus diseases and those of manganese deficiency. Also there are some plants which have normally variegated foliage. It is difficult to correctly diagnose manganese deficiency by the appearance of such a plant. In such cases it may be necessary to resort to the use of a laboratory test for manganese on fresh plant tissue.**

Small Grains and Grasses

Many members of the grass family have been shown to be sensitive to a lack of manganese. Perhaps oats are the most sensitive of the grains. When oats are grown in a medium deficient in man-

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**Journal of Agricultural Research, 24*: 781–794, 1923.
***Soil Science Society of America Proceedings, 8*: 327–328, 1944.

ganese, they develop the "disease" called "grey speck." This is not a pathological disease, but is simply a physiological breakdown of the leaf tissue. It was first reported in this country by Sherman and Harmer* in 1941.

"Grey speck," illustrated in Fig. 41, starts as a grey oval-shaped spot on the edge of a new leaf. It usually appears when the plant

Fig. 41. (see color plate section, page 81)

has reached the stage when it has three or four leaves. The grey speck appears some distance back from the tip and gradually enlarges until it spreads across the entire leaf. As the spot enlarges, the

Fig. 42. Wheat grown on Granby sandy loam, an alkaline sandy soil rather high in organic matter. The left pot received manganese sulfate at the rate of 100 pounds per acre. Note the light color of the wheat which did not receive manganese. Note also that the leaves droop in a manner similar to the oats leaves shown in Fig. 44.

Journal of American Society of Agronomy, *33*: 1080–1092, 1941.

Fig. 43. Barley grown on Granby sandy loam. The right pot received manganese sulfate at the rate of 100 pounds per acre. The picture shows the untreated plants to be much lighter in color and to have drooping leaves as do the oats plants shown in Fig. 44.

Fig. 44. Oats are extremely sensitive to a deficiency of manganese. These plants were grown on Granby sandy loam soil.

Left—Manganese sulfate at the rate of 100 pounds per acre.
Right—No manganese.

grey color gradually gives way to yellow. The yellow color finally extends over a considerable length of the leaf. At about the time the affected area has reached the full width of the leaf, the leaf droops, leaving the yellowed portion sticking up where it helps to give the field, or perhaps a spot in the field, a yellow appearance. During all this time the *tip* of the leaf remains green. This is an important point to remember, because it positively proves that the symptom is not that of nitrogen or potassium deficiency.

An examination of Figs. 42 and 43 shows that wheat and barley are also very sensitive to a deficiency of manganese in the soil. The symptoms are somewhat different from those in oats. Instead of the appearance of the characteristic grey speck, the upper leaves simply start turning yellow in streaks parallel to the length of the leaf. Some of the streaks become wider in places, so that the leaf has a spotted appearance. The leaf tip does not remain as distinctly green as do

the tips of oat leaves. The yellowing does not, however, start at the tip as it does on plants deficient in nitrogen or potassium. The leaves of barley and wheat plants droop in much the same manner as do those of oats. This is shown by comparing Figs. 42 and 43 with Fig. 44.

On alkaline soils, especially if they are sandy, sudan grass may be very responsive to applications of manganese. This is illustrated by Fig. 45. The symptoms of deficiency resemble closely those in wheat and barley, a yellow striping and spotting of the upper leaves with a general light-green color over the entire plant.

Beans

Beans, including white field beans, soybeans, and garden beans, are similar in appearance when grown on soils insufficiently supplied with available manganese. Shortages of manganese for these crops occur on soils with a pH above 6.5 and are more serious on sandy than on heavy soils. The right leaf shown in Fig. 28 is typical of those deficient in manganese. Note that the yellowing is uniform over the

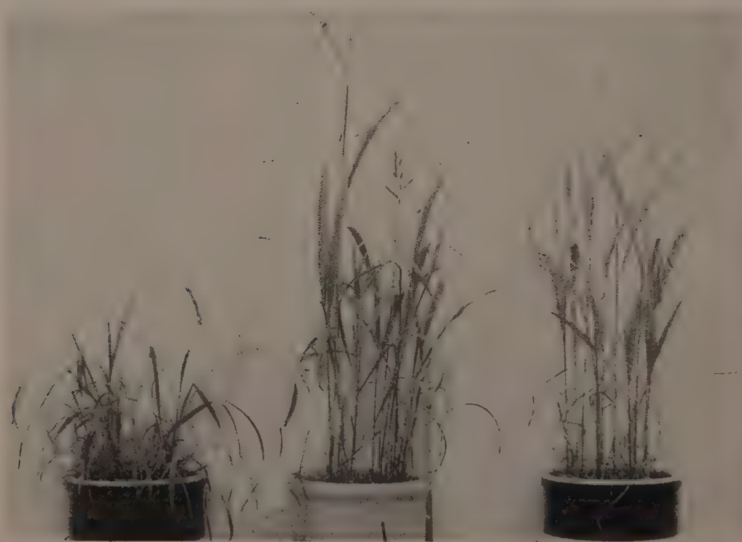

Fig. 45. On soils deficient in available manganese, an application of manganese sulfate may greatly stimulate the growth of sudan grass.

Left—No manganese.

Center—Manganese sulfate at the rate of 50 pounds per acre.

Right—Manganese sulfate at the rate of 100 pounds per acre.

entire leaf and that the veins remain green. Compare its appearance with that of the potassium-deficient leaf in the same picture.

On some of the very sandy alkaline soils, manganese deficiency in white field beans and soybeans shows up very early, often on the first pair of leaves. On some of the better alkaline soils, the symptoms appear later in the stage of growth. On such plants it is the *new growth* that is affected. This is in contrast to nitrogen deficiency, which shows up first on the lower, older leaves.

In fields where symptoms have appeared early in the season, side-dressings of manganese sulfate at the rate of 100 pounds per acre have caused very profitable increases in yield. Applied beside the seed at planting time, smaller applications are satisfactory. Spraying deficient plants with as little as 5 pounds per acre in 200 gallons of water has furnished manganese sufficient for normal growth.

Garden beans are very sensitive to a lack of manganese. Many garden soils are alkaline because they have been irrigated with hard water. In such soils, some effort should be made to supply beans with soluble manganese. In Fig. 46 is illustrated the effect of spraying

Fig. 46. (see color plate section, page 82)

garden beans on the Pett farm near Bay City with 5 pounds of manganese sulfate per acre. The soil was naturally alkaline. The owner observed an improvement in quality as well as an increase in yield of beans from the treated row.

Sugar Beets

Sugar beets are commonly grown in Michigan on soils deficient in available manganese. The deficiency may show up in the plant at any time during the growing season and is first noticed as a mottling of the new growth. The green color gradually fades from the leaf tissue between the veins. The veins themselves and the area closely adjacent to the veins remain green for a considerable period after the rest of the leaf is yellow. The Number 1 leaf shown in Fig. 47

Fig. 47. (see color plate section, page 82)

was typical of beet leaves badly deficient in manganese. Sometimes the veins are much less distinct. In fact it is occasionally difficult to distinguish the mottling. In such cases there is a possibility of confusion between manganese and nitrogen deficiency. One should

then resort to the use of the green-tissue test for nitrate nitrogen. This should be made on the leaf petiole. If the test is positive, it is safe to assume the yellowing is due to something other than nitrogen. Whenever manganese deficiency is suspected, it is always wise to determine the reaction of the soil.

Other Crops

Manganese deficiency has been observed in several other crops and in various shrubs and weeds. With all plants the pattern is the same, light green to yellow areas between dark veins. The trouble is always associated with neutral, or only very slightly acid, to alkaline soils.

Alfalfa and the clovers are much less sensitive to manganese deficiency than are oats, beans, and sugar beets. Good crops of alfalfa have been observed on fields where oats failed from a lack of manganese during the previous season.

Manganese deficiency has been observed on tomatoes, potatoes, strawberries, and peaches, but more experimental work needs to be done before recommendations regarding these crops may be made.

BORON DEFICIENCY

Boron is not plentiful in Michigan soils. It occurs mostly as a constituent of the mineral "tourmaline" and in organic matter. The total quantity of boron in a soil seems of little importance. The important point, so far as plants are concerned, is its availability. Observations and experiments have shown that boron deficiency in this state occurs only on soils high in lime, either on those naturally alkaline or where too much lime has been applied. It is possible to induce boron starvation by applying lime in excessive amounts to an acid soil, or to prevent the deficiency from appearing by adding sulfur or sulfuric acid to an alkaline soil.

In previous publications the writers* and others** have discussed the subject of boron availability and fixation. Further work is now in progress on these subjects, so no attempt will be made to discuss them in this bulletin. It is sufficient to say that boron is usually not needed on soils that need lime.

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*_Soil Science Society of America, Proceedings, 4_: 297–301, 1939.

**Parks, R. Q., and Shaw, B. T., "Possible mechanisms of boron fixation in soil: 1 Chemical," _Soil Science Society of America, Proceedings, 6_: 219–223, 1941.

The exact role of boron in plants is somewhat obscure. It seems to function chiefly as a regulator of the intake of other ions. Various investigators have reported certain ratios between quantities of boron taken in by plants and the intake of such elements as calcium and potassium. It is known, of course, that calcium affects the intake of certain other elements, so if boron affected calcium intake it would indirectly affect the intake of all ions affected by calcium.

A deficiency of boron causes a breakdown of the young growing tissue. Growth slows down, and in many plants the cells actually disintegrate, causing the tissue to crack, blacken, and become abnormally shaped. With alfalfa, internodes are shortened and the buds fail to open. Although boron is essential for plant growth, only small quantities are needed, and the amount varies greatly for different plants. An excess is extremely toxic and may affect different plants in different ways. With some plants, soybeans for instance, the growing tissue may be over-stimulated so the plant makes a tall, spindling growth. Characteristic brown spots develop on the edges of the leaves, and the older leaves are shed early. Corn injured by an excess of boron is stunted, and the leaves turn grey along the edges.* Barley, so injured, develops brown spots about ⅛ inch long and about half as wide which are well scattered over the leaf. The spots are actually dead tissue, and they persist to the time of maturity. Peas turn brown at the tips and around the edges of the leaflets, and alfalfa leaves turn white across the ends when borax is applied in excess. Under certain conditions, 40 pounds of borax per acre will be toxic to alfalfa, while a much smaller quantity will injure beans, barley, peas, and corn.

Sugar Beets

Boron deficiency of sugar beets has for many years been termed "heart rot." It was so called long before it was realized that a lack of boron caused the "disease." Investigators in Germany and France spent many years trying to isolate an organism responsible for the death of the heart tissue. Of course they were not successful, and in 1931 Brandenburg of Germany showed that the "disease" could be prevented by adding soluble boron to the soil. Heart rot was observed in Michigan by Kotila** in 1934 and has been discussed by

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*The writers are indebted to H. J. Guist for specimens of corn injured by an excess of borax.
***Facts About Sugar, 30*:373–376, 1935.

Fig. 48. Boron-deficient sugar beet with a typical dead heart. Only one old leaf was still alive. Notice the new leaves coming out from the edge of the crown. Such new leaves may attain normal size, or they may become deformed and remain small, depending on how seriously the beet is affected.

the writers* in previous publications. A few pictures will make it easy to distinguish heart rot in the field.

There are several rather specific and different symptoms of boron deficiency, all of which may or may not occur in the same plant. Some plants may have both top and root symptoms, while some may have top symptoms only and others may have only root symptoms.

The most noticeable symptom, of course, is the dead heart illustrated by Fig. 48. This is first noticed during midsummer, after the beet has attained considerable size. The leaves may all die. On severely affected fields, the crop may appear almost entirely defoliated by the end of the summer. Some beets actually die, but most of them make new growth during the early fall months, until new leaves from around the edge of the crown may almost cover the dead heart.

Soil Science Society of America, Proceedings, 5:227–234, 1940.

Perhaps the first symptoms of heart rot are cross-checked petioles and misshapen leaves, illustrated in Fig. 49. The leaves seem to grow unevenly on the two sides. This causes the petioles and midribs to twist and the leaf to develop only on one side. There is also a tendency, as shown in Fig. 50, for the development of a large number of small leaves, few of which ever reach normal size.

Boron-deficient beets also give one the impression of having been stepped on. The leaves grow out in a horizontal rather than in the normal vertical position. Their color is dark green until they start to disintegrate, when they turn yellow, brown, and black.

The roots of sugar beets affected by heart rot vary greatly in the extent to which they break down. In fact, some plants show by their leaves that a deficiency of boron exists while their roots appear perfectly normal. Usually, however, the root tissue turns black and disintegrates to various degrees. In some cases the whole crown breaks down, while in others the disintegration is scattered throughout the beet. When the disintegrated areas break through the surface, they appear as external cankers. A good idea of the appearance

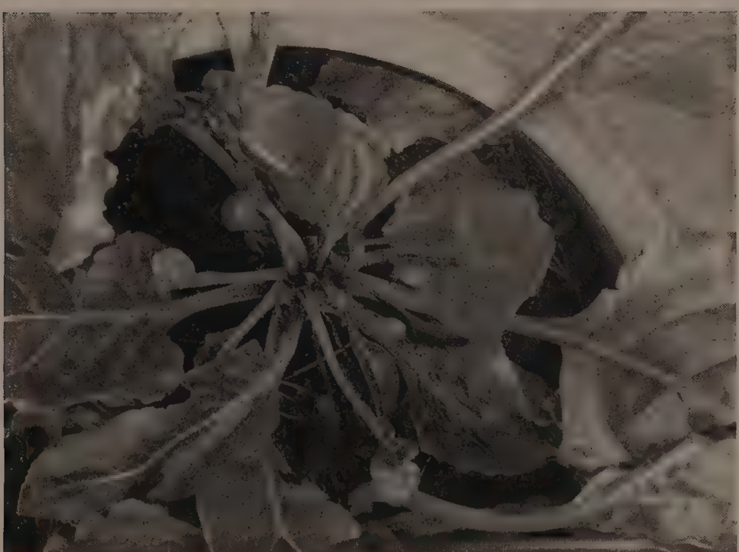

Fig. 49. Cross-checked petioles and misshapen leaves, curved to one side, are early symptoms of heart rot of sugar beets.

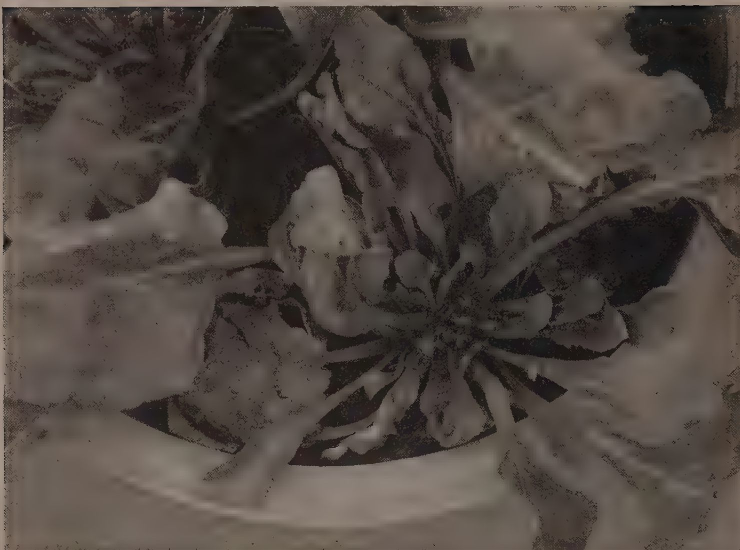

Fig. 50. Sugar beets with heart rot sometimes produce numerous small leaves, few of which reach normal size. Most of the leaves on this beet were misshapen.

of sugar-beet roots deficient in boron may be obtained from Fig. 51.

Sugar beets are so sensitive to a deficiency of boron that one should include borax in the fertilizer for beets on all soils, although it is only on the alkaline soils that heart rot has been found serious. Where the fertilizer is placed in bands beside the seed or in contact with the seed, the rate of application need be only 7 to 10 pounds per acre. More than that quantity may be toxic if placed in direct contact with seed.

Table Beets

Table beets are also very sensitive to a deficiency of boron. The symptoms are not unlike those of sugar beets, although the dead heart is not so common. The cross-checked petioles and twisted leaves may be observed on the plant shown in Fig. 52.

The roots of table beets deficient in boron commonly develop what have been termed "internal black spots." These spots occur anywhere throughout the fleshy portion of the root, and if they happen to occur very close to the surface they break through the epidermis to form external cankers, as shown on the beet pictured in Fig. 53.

Fig. 51. Boron-deficient sugar beet roots. Such roots vary greatly in the degree to which they break down. In some cases the internal tissue turns black but remains firm while in others it disintegrates to a considerable extent. Sometimes the crown disintegrates to the extent that the plant dies. Where the disintegration is near the surface it breaks through the epidermis of the root and forms an external canker as is shown on the beet at the right.

Fig. 52. Table beet deficient in boron. Note the cross-checked petioles and twisted leaves, so common on sugar beets deficient in boron.

Fig. 53. (see color plate section, page 83)

The blackened areas contain cork tissue, developed apparently by the plant to set off the disintegrated cells from the healthy cells. When the beets are cooked, the black spots are even more pronounced than before cooking, and between the teeth they actually feel like cork. Some cooked slices of boron-deficient beets are shown in Fig. 54.

Fig. 54. (see color plate section, page 83)

Boron deficiency of table beets, as with sugar beets, occurs on alkaline soils. Where the fertilizer for beets on such soil is applied broadcast before planting, it is recommended that the quantity of borax applied be 40 pounds per acre.

Spinach

The spinach plant is closely related to the sugar beet and, in its manner of growth, closely resembles the sugar beet. The symptoms of boron deficiency are also similar in the two plants.

In an experiment conducted on boron-deficient, Thomas sandy loam soil, the spinach from plots which did not receive borax in the fertilizer looked like the plant shown in Fig. 55. In Fig. 56, it may be seen that the individual leaves were small and developed on one

Fig. 55. (see color plate section, page 83)

Fig. 56. Spinach leaves. Those on the left were from a boron-deficient plant. Note the abnormal size and shape. The right leaf was from a plant which was grown on a plot treated with borax at the rate of 10 pounds per acre.

side. The roots were blackened in much the same manner as is characteristic of sugar beets with heart rot.

Mangels

The mangel, a close relative of the sugar beet, is also very sensitive to a deficiency of boron. The symptoms of deficiency are the same except that the mangel does not develop the cross-checked petioles as does the beet. Normal and boron-deficient mangel roots are shown in Fig. 57.

Fig. 57. Mangel roots, normal on the left and deficient in boron on the right. The tissue breakdown is not unlike that observed in sugar beets and red beets.

Head Lettuce

In the experiment on Thomas sandy loam already referred to, lettuce on the plots which did not receive borax failed to head. The new center leaves became black and ill-shaped while yet small. On the plots where 10 pounds or more of borax was applied, the heads were normal in appearance and of good quality. The effect of the borax is illustrated by Fig. 58.

Fig. 58. (see color plate section, page 83)

Cauliflower

Members of the mustard family, of which cabbage and cauliflower are common examples, need plenty of boron. When it is

lacking, the inside of the stalks disintegrates, and the heads turn brown. The boron-deficient cauliflower plant shown in Fig. 59 was cut to expose the disintegrated stalk. The browning of the head is likewise noticeable in the picture. The stalks of cabbage also break down at the heart when boron is deficient.

Fig. 59. (see color plate section, page 84)

Celery

Crack stem of celery, first called "marl disease" because it was associated with the growth of celery on organic soils underlaid by marl, is caused by a lack of boron. The association between crack stem and boron deficiency was described by Purvis and Ruprecht* in Florida and by Harmer** in Michigan. Recommendations for the prevention of crack stem on Michigan's organic soils have been published by Harmer. Crack stem is illustrated by the celery plant shown in Fig. 60.

Fig. 60. (see color plate section, page 84)

Other Crops

Boron deficiency has been observed on several other crops in Michigan. Rutabagas and turnips develop water-soaked areas where the cells have broken down. The disorder has been called "water core."

Chicory leaves turn red and tend to grow with twisted midribs when boron is lacking. Apparently this tendency for petioles and midribs to twist is common with many plants when boron is deficient.

Alfalfa has been shown by investigators in certain other states to be very sensitive to boron deficiency, but in Michigan it is not considered a crop which commonly needs boron. The deficiency is indicated by a yellowing and bronzing of the leaves and by a restriction of the terminal growth, which produces very short internodes. Affected plants fail to flower. Leaf hoppers cause yellowing and bronzing of alfalfa leaves but do not cause the internodes to shorten.

**Florida Agricultural Experimental Station*, Bulletin 307, 1937.

***Michigan Agricultural Experimental Station*, Special Bulletin 314, 1941.

Certain crops are easily injured by even very small quantities of borax. Chief among these are beans, soybeans, and peas. As little as 1.8 pounds of borax per acre applied directly with the seed of field beans has been known to cause very serious injury. The small grains and corn are also easily injured by applications of borax.

Even these crops which are so easily injured by borax do, however, need a small amount of boron. In greenhouse tests, the writers have been able to demonstrate increased growth of small grains and corn by applying a small amount of borax to a boron-deficient soil.

MAGNESIUM DEFICIENCY

Magnesium occurs in the soil as primary and secondary minerals and as exchangeable ions attached to the clay particles. During the process of soil formation the magnesium, along with other basic cations (calcium, potassium, and sodium), is released from the minerals. The magnesium ions then unite with other ions to form secondary insoluble compounds, or they may be used by plants or may become attached to the clay particles.

The capacity of the clay particles to absorb cations depends upon the nature of the clay; the degree to which the clay is saturated with the basic cations determines the pH of the soil. The chief basic cations in a humid region soil are calcium and magnesium. As soils become excessively leached, the total basic cation concentration becomes reduced and the concentration of hydrogen ions is correspondingly increased. Such soils are said to be acid.

The concentration of mineral nutrients (basic cations) may thus become so low in acid soils as to be insufficient for normal plant growth. In some cases it may be necessary to supplement all the mineral nutrients. In other cases, owing to differences in parent material and the nature of weathering, the nutrients are unbalanced with respect to each other. Furthermore, past management practices may have brought about an unbalanced nutrient status. Soils become acid as a result of the loss of several basic ions. The addition then of large quantities of calcium lime such as calcium carbonate or marl brings about an unbalanced condition, with calcium high in proportion to magnesium and potassium.

Excessive applications of potash fertilizer have been known to cause a deficiency of magnesium, as has also the application of sodium, either as the nitrate or the chloride. Walsh and O'Donohoe*

*Journal of Agricultural Science, 35: 254–263, 1945.

found that applications of 500 pounds sulfate of potash per acre significantly reduced the percentage of magnesium in potatoes, sugar beets and tobacco, and caused serious magnesium deficiency symptoms. Hale, Watson and Hull** showed by pictures that sodium chloride induced magnesium deficiency symptoms in sugar beets. Prince, Zimmerman, and Bear*** observed that magnesium deficiency symptoms were present on New Jersey crops when magnesium constituted less than 6 percent of the exchange cations in the soil and that the ideal amount of magnesium in the soil was an amount equal to 10 percent of the exchange capacity. Thus, one may expect to encounter magnesium deficiency on very acid soils, on soils limed with calcium lime or on soils heavily treated with potassium- or sodium-bearing fertilizers.

Magnesium is the only mineral element contained in chlorophyl, the pigment which makes plants green. It is not surprising then that magnesium deficiency should result in chlorosis. Perhaps, however, the tendency is no greater than it is for deficiencies of the other elements already discussed—potassium, phosphorus and manganese—which are not constituents of chlorophyl.

Truog, Goates, Gerloff and Berger**** have emphasized the role which magnesium plays as a carrier of phosphorus in plants. They obtained a greater increase in the phosphorus content of peas by adding magnesium sulfate than by increasing the concentration of phosphorus in the culture medium. In the field they obtained marked increases in the phosphorus content of dry peas by adding dolomitic limestone. In their conclusions they state that "Failure in many experiments to produce crops of higher phosphorus content through phosphate fertilization has undoubtedly been due to a lack of available magnesium."

Symptoms of magnesium deficiency first appear on the older leaves. This shows that the element, like nitrogen, phosphorus, and potassium, is readily translocated from old to new tissue. Yellowing appears in patches between the veins and around the leaf edges. The edge yellowing is not so prominent as is the case with potassium deficiency, especially from the viewpoint of demarcation between yellow and green. Leaf edges usually roll slightly.

As the magnesium-deficient leaf becomes older, the yellow areas

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***Annals of Applied Biology, 33:* 13–28, 1946.
****Soil Science 63:*69–78, 1947.
*****Soil Science 63:* 19–25, 1947.

scattered over the leaf blade become necrotic until finally the tissue may disintegrate to leave holes through the leaf. Prominent green veins may accompany the mottling, in much the same pattern as has been described for potassium deficiency. There need be no confusion with manganese deficiency because in the latter, the yellowing is uniform over the entire leaf or leaflet.

Magnesium deficiency in Michigan has been observed on celery, sugar beets, potatoes, field beans, and corn. Further work now in progress will show how serious the deficiency may be on these and other crops.

Celery

Davis and McCall* have described magnesium deficiency in celery as a mottling which starts on the tips of the older leaves. Yellowing then progresses around the leaf margins and inward between the veins. Veins stand out clearly and necrotic spots soon appear between them. The appearance of such leaves is illustrated by Fig. 61. Some varieties were more susceptible to magnesium deficiency than

Fig. 61. Celery leaflets: magnesium-deficient (left) and normal.

were others. The Utah 10-B was most susceptible, while Utah 15 showed no evidence of the deficiency. Emerson Pascal and Utah 52-70 varieties were intermediate so far as susceptibility to the deficiency was concerned. The deficiency was controlled by an ap-

*Michigan Agricultural Experiment Station Quarterly Bulletin, 35: 324–329, 1953.

plication, as a spray, of 10 pounds per acre of magnesium sulfate every 10 days during the growing season.

Sugar Beets

Magnesium deficiency symptoms in this crop are quite similar to those of potassium deficiency. The chief difference lies in the fact that chloratic areas appearing within the central portion of the leaf

Fig. 62. Sugar beet leaves. Numbering from left to right. 1. Normal. 2. Magnesium deficient. Note the necrotic patches throughout the leaf and slightly yellow leaf margin. 3. Iron deficient. Note green veins on a *uniformly* yellow background. 4. Manganese deficient.

soon become necrotic as shown in Fig. 62. As the leaf is moved by the wind the necrotic tissue breaks out, with holes resulting.

Sugar beets are largely grown in Michigan on slightly acid-to-alkaline soils, where the total quantity of magnesium is fairly high. However, the crop is heavily fertilized with potash and sometimes with salt, so it seems desirable to pay attention, in the future, to the need of the crop for magnesium. Symptoms of deficiency may indicate where magnesium should be included in the fertilizer.

CALCIUM AND IRON DEFICIENCIES

These two elements are discussed together because the symptoms of deficiency are almost identical. Calcium occurs in the soil in the same kind of combinations as does magnesium. The chemistry of the two elements is similar. They should be in the soil, in available form, in a rather definite ratio, variable to some extent for different crops, but generally in the neighborhood of 1 part of magnesium to 10 of calcium. The elements differ widely, however, in their functions within the plant and in the way their absence affects the plant.

Calcium becomes a part of cell walls and plays an important role in regulating the pH of the cellular tissue. The element is *not* translocated from old to new tissue. Accordingly, the first symptoms of deficiency occur on the youngest leaves. Even before the leaves unfold they are chlorotic, uniformly so, with prominent green veins. The spinach plant shown in Fig. 63 illustrates in a characteristic

Fig. 63. Calcium-deficient spinach plant, the deficiency having been induced by an excessive application of magnesium sulfate.

fashion the appearance of a calcium-starved plant. In this case the calcium deficiency was induced by an excessive application of magnesium sulfate.

Strongly acid soils are low in degree of base saturation. The soybean plants shown in the left pot in Fig. 64 were not obtaining suf-

Fig. 64. Soybeans respond to lime. The Fox sandy loam soil in the left pot had a pH of 4.7. The chlorotic new leaves were typical of calcium-starved plants. The lime application raised the pH in the right pot to 5.8.

ficient calcium from the strongly acid Fox sandy loam. Where lime was applied the symptoms were not present.

Iron occurs in soil quite largely as the oxide or hydrated oxide. When highly oxidized the iron is not available to plants. Iron, like calcium, is *not* translocated from old to new tissues. The visible symptoms of deficiency are identical with those for calcium deficiency. Iron deficiency in sugar beets is illustrated by one of the leaves shown in Fig. 62. By making use of the pH test on the soil, one can easily differentiate between calcium and iron deficiencies. In Michigan, calcium deficiency occurs only on *acid* soils, unless an excessive quantity of some other basic cation has been applied. Iron deficiency, on the other hand, occurs only on *alkaline* soils. It is most common on shrubs, garden crops, and greenhouse plants watered with hard water. Growers of gardenias, greenhouse roses, and other acid-loving plants find it necessary to spray their plants with ferrous sulfate to avoid iron deficiency, commonly called "lime chlorosis."

Green-tissue Tests

Tests on green plant tissue indicate, in a roughly quantitative way, whether or not a plant is getting sufficient nutrients to satisfy its needs *at the moment the test is made.* The tests are for soluble nutrients in the plant, and they are possible because plants take in more nutrients, when supplies are ample, than they currently assimilate. This leaves an accumulation in the plant. This tendency of plants to store up nutrients is spoken of as "luxury consumption." When the test for a certain nutrient, nitrate for instance, is strongly positive, the conclusion is that the supply of nitrate in the soil is, at that time, ample for the needs of the particular plant or plants tested. On the other hand, when the test is blank, one must conclude that the plant is assimilating the nitrate (building it into plant tissue) as fast as it takes it in and that all stored nitrate is used up. The conclusion then is that the supply of nitrate in the soil is either just sufficient for the needs of the plant or that it is inadequate. The appearance of the plant usually indicates which of the two conditions exists.

EXPERIMENTAL TESTS

To ascertain the soundness of the tissue-testing idea and to check the use of the Spurway soil-testing equipment for making the tests, sugar beets were grown in 2-gallon glazed pots to which was applied, in addition to other elements, nitrogen at ten different levels. The rates of application were from none to 1000 pounds per acre at increments of 100 pounds. Nitrate tests were made on the leaf petioles at frequent intervals until the test results were blank on the beets which received less than 700 pounds an acre of NH_4NO_3. This occurred 107 days after the beets were planted. On that day, all beets which had received less than the 700 pounds an acre of NH_4NO_3 were taking in so little nitrate that there was no accumulation in the leaves. The conclusion then was that a larger application of nitrate would have caused a greater growth. On the other hand, the beets which received 700 or more pounds per acre of NH_4NO_3 were still taking in enough nitrate so they could accumulate some in the leaves. For that reason, additional nitrogen should not have caused further increase in yield. The curve shown in Fig. 65 indicates that such was actually the case. The beets which received 700 pounds

of nitrogen fertilizer per acre produced the greatest yield. The curve indicates that, while amounts greater than 700 pounds seemed to be injurious, any quantity less than 700 pounds was insufficient to meet the needs of the plants, exactly as was indicated by the tissue tests on the day of harvest. There seems to be no plausible explanation as to why the yields caused by the 500-pound and 800-pound applications were out of line with the others.

To verify these results, the experiment was repeated on the same type of soil using the same treatments. In the second trial, it re-

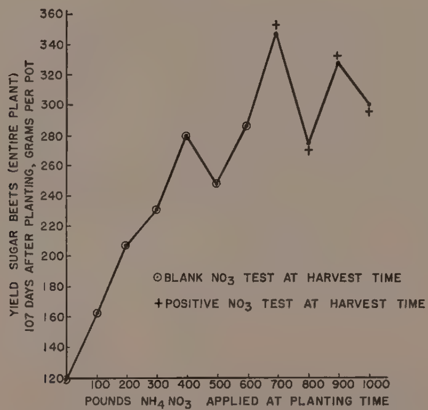

Fig. 65. The effect of ammonium nitrate on the yield of sugar beets and the nitrate content of the beet tops, first trial.

quired 142 days for the nitrate to become deficient in all pots which had received 600 or less pounds per acre of NH_4NO_3 fertilizer. Furthermore, the total yields were smaller. This is believed, however, to be due to the season. In the first trial, planting was on Feb. 7, and in the second on Nov. 23. Despite the difference in season, the results obtained in the second trial, as shown in Fig. 66, were very similar to those already discussed. The yields obtained from the beets which received 700 pounds per acre of nitrogen fertilizer, and which had shown no lack of nitrate up to harvest time, were greater than were any of those which had received less than 700 pounds.

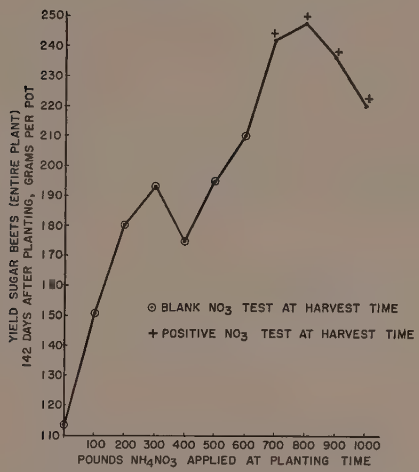

Fig. 66. The effect of ammonium nitrate on the yield of sugar beets and the nitrate content of the beet tops, second trial.

It is true that in this second trial the yield did increase a little on the pots which received 800 pounds of fertilizer per acre. This would not have been predicted from the tissue tests, but it is believed that the difference in yield, apparently caused by the eighth 100-pound increment of fertilizer, was not significant. Again in this trial, the yield resulting from one treatment, that of 400 pounds of fertilizer per acre, was out of line with the others. No explanation is available.

Many instances could be cited where tissue tests have been conducted on plants grown in fertilizer experiments that would prove the tests to be reliable when properly conducted and interpreted. For instance, in the spring of 1946, phosphate and potash fertilizers were applied, singly and in combination at the rates of 150 pounds of P_2O_5 and K_2O per acre, on 66 fields of alfalfa or clover. The fields were located on several types of soil scattered well over the state. Just prior to harvest, tests for phosphorus and potassium were made on the green stems of the plants. In almost all cases where there was a response to phosphate, the test for phosphorus was higher on phosphate-treated plots than on untreated plots or on plots which received only potash. In fact, there were many instances where the

phosphate content of plants from the potash-treated plot was lower than that of plants from the untreated plot. This was because of greater utilization of phosphate as a result of the growth stimulation caused by the potash.

A similar condition was found to exist in regard to the potassium content of plants grown on untreated plots and plots treated with potassium or phosphorus. With few exceptions, it was possible to identify the potash-treated plot by the potassium test on the green plant tissue.

In greenhouse-pot-culture experiments, tissue tests for nitrate, potassium, and phosphorus have been found to correlate very well with treatments and with the occurrence of deficiency symptoms. In at least two instances, suspected errors in treatment have been positively clarified by the tissue tests.

METHODS OF TESTING GREEN TISSUE

Two methods of green-tissue testing have been used extensively at this station. The Purdue method* has been found suitable and is recommended for those who prefer to use it. In the opinion of some investigators, it has the advantage of having been designed for use with color charts which are provided with the testing outfit.

The Spurway Simplex** soil-testing outfit may be used for testing green tissue. The reagents and glassware provided for testing soil serve equally well for testing green plant tissue.*** The tests are sufficiently simple to permit their use by anyone who has used the equipment for testing soil. As with soil tests, there is a possibility of error in the interpretation of the tests. Perhaps a word of warning is advisable regarding one error which is common.

Plants are generally found to be lower, relatively, in one element than in all others. That element, of course, is the one lowest in the soil in available form and is generally spoken of as the "first limiting factor" in crop production. Say, for instance, that on some particular soil the first limiting factor is nitrogen and the plants are showing symptoms of nitrogen starvation. The tissue test for nitrate nitrogen will be blank, but the tests for phosphorus and potassium may be high. In fact, they are likely to be high, even higher than in normal *rapidly* growing plants. The tests do not mean, though, that the

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**Purdue Univ. Agr. Exp. Sta. Cir. Bul.*, 204 (revised), 1939.
***Mich. Agr. Exp. Sta. Tech. Bul.*, 132 (3rd revision), 1944.
***In the phosphorus test, stannous chloride is better than metallic tin.

soil contains sufficient phosphorus and potassium for a normal crop, but only that *it contains enough for a crop stunted by a shortage of nitrogen*. As soon as nitrogen is applied to a crop, under such conditions, growth is stimulated, and often another element, perhaps phosphorus, becomes the first limiting factor. There is a possibility, of course, that a soil might be extremely low in available nitrogen and actually contain sufficient phosphorus and potassium for a normal crop. Soil tests should make it possible to tell when that condition exists.

Manganese, an element often deficient in alkaline soils, may be tested for in green leaves, but the method* requires laboratory facilities and so is not considered a quick test which may be performed with the Simplex outfit. By a process of elimination, and because symptoms of manganese deficiency are rather specific and easily distinguished, it is usually possible to avoid the necessity of testing for manganese.

Directions for Making Green-Tissue Tests With Spurway Simplex Soil-Testing Kit

Tests should be made on fresh tissue only. By keeping plants moist and in a refrigerator, they may be stored for a day or two before the tests are made. They cannot be made after the tissue has dried. Leaf blades contain too much pigment for best results. In general, it is better to use thinly sliced sections of stems or leaf petioles. The mobility of the element within the plant should be considered in deciding what portions of the plant to use in making the tests.

Nitrogen—Place the thinly cut sections of plant tissue in the depression of a spot plate. Apply several drops of Reagent 2. With large pieces of plant tissue, like those obtained from the stalk of a corn plant, simply drop the reagent on a freshly cut surface. If nitrate is present in the plant tissue, the reagent will turn blue. If the blue color is faint and *slow to form*, the test is low and the plant is about to run out of nitrate. If the blue color develops quickly and is very dark, the test is very high and the nitrate supply of the plant, as of that date, is sufficient. One should not confuse a brown color with a blue color. Figure 67 shows the results of the nitrate test on

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corn. Note the brown color of the reagent on the stalks low in nitrate.

Fig. 67. (see color plate section, page 84)

Phosphorus—Place 1 cc. of thinly sliced plant tissue in a small glass vial (fill the vial to the first graduation). Fill the vial one-half full of distilled water and shake for 1 minute. Add 5 drops of Reagent 3, shake, and add a speck of stannous chloride, perhaps about the size of a pin head. Shake and wait about 2 minutes, not longer than 5 minutes, for the color to develop. It is well to add a little more stannous chloride to see whether the color deepens. Too much stannous chloride causes the color to be green instead of blue. A deep blue color means a high test and is an indication that the plant was obtaining sufficient phosphorus at the time the sample was taken. A very light blue, as in the center vial shown in Fig. 68, indicates that the phosphorus supply is not sufficient.

Fig. 68. (see color plate section, page 84)

Potassium—Place 1 cc. of thinly sliced plant tissue in a small glass vial (fill the vial to the first graduation). Fill the vial one-half full of *cold* (below 20°C.) distilled water. Shake for 1 minute. Add 3 drops of Reagent 5, shake, and add 2 cc. of Reagent 6. The Reagent 6 should be cold unless the distilled water is cold enough so the mixture of distilled water and alcohol (Reagent 6) will be below 20°C. Shake and estimate the density of the precipitate by holding a heavy black line on white paper back of the vial. If the line is not visible through the solution, the test may be considered high and the indication is that the plant was obtaining sufficient potassium at the time the sample was taken. If the line is sharply distinct, the test is blank. This, of course, indicates that the plant was starved for potassium at the time the sample was taken. If the black line is easily visible but blurred in outline, the test is low. A faintly visible line through the solution may be considered an indication of a medium supply of potassium. Illustrations of the test results may be obtained from Figs. 22 and 27.

Portion of Plant to be Used in Tests

In deciding what portion of a plant to use for green-tissue tests, it should be remembered that all three of the elements nitrogen,

phosphorus, and potassium are readily translocated from old to new tissue. For that reason, it is sometimes desirable to test both old and new tissue. Usually it is sufficient to test the old tissue. If the test there is high, it is safe to assume that a high test will also be obtained on the new tissue. If the old tissue tests low, however, there is a chance that new tissue may test high. Such results indicate that the plant is just on the verge of becoming deficient in that nutrient element.

The parts of the plants most suitable for testing for a few crops are as follows:

Beets	leaf petioles	Soybeans	leaf petioles
Corn	leaf sheath*	Potatoes	leaf petioles or stem
Grains	stem		
Alfalfa	stem	Tomatoes	lower leaf petioles
Beans	leaf petioles	Geranium	leaf petioles

*Use the stalk in the case of very young plants.

Importance of Comparative Tests

The results obtained from green-tissue tests are most useful when they are expressed on a comparative basis. Plants vary somewhat in the quantity of nutrient they may contain at the time when they show indications of being starved. For this reason it is always advisable to make tests on deficient and normal plants *at the same time*. In other words, if a test is to be made for phosphorus on some plant where phosphorus deficiency is suspected, test at the same time a plant which is known to contain *plenty* of phosphorus. This is usually possible by taking plants from other fields or from treated plots. After one has made many tests, such a comparison becomes less important.

Summary

The higher plants, with a few exceptions, are supposed to be green. Any force or circumstance which interferes with normal metabolism results in failure of the plant to manufacture the usual amount of chlorophyl. The yellow pigment, always present, is then noticeable. Yellowing may be due to the ravages of diseases or insects. More often, however, it is due to a deficiency or excess of some nutrient.

All deficiencies sooner or later result in chlorosis. By noticing the pattern of yellowing and where it first appears on the plant, and/or by making certain soil and plant tissue tests it is possible to decide

which element is deficient. Likewise, the presence of nutrient excesses may be ascertained.

A shortage of nitrogen results in a uniform yellowing of older leaves, and in many plants an increase in the development of anthocyanin pigment, especially in leaf petioles and veins and in stems. In potassium-starved leaves, on the other hand, there is sharp contrast between yellow and green on the same leaf and between new and old leaves.

Phosphorus deficiency is characterized by dark green seedlings, sometimes with an increase in anthocyanin, generally in leaf blades, and by yellowing of older leaves as maturity approaches. Excessive leaf drop is common.

Boron deficiency results in a breakdown of the meristern (growing) cells. New leaves are often small and abnormally shaped. The color of young plants is usually dark green. Chlorosis develops as the plants approach maturity.

A lack of magnesium causes plants to resemble those starved for potassium except that chlorosis—and later, necrosis— shows up as patches throughout the leaf blade as well as around the edge.

Manganese, calcium, and iron deficiencies show up on broad-leafed plants as uniform chlorosis between green veins. In the case of manganese, the symptoms appear first on leaves which are just slightly older than the newest ones, whereas iron starvation shows up on the very newest leaves. They are chlorotic even before they unfold or emerge. Both deficiencies are common on *alkaline* soils.

Calcium-deficiency symptoms are exactly like those caused by a lack of iron. It is possible to differentiate between them only by determining the pH of the soil. In Michigan, calcium deficiency occurs only on *acid* soils.

Acknowledgment

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Fig. 1a. Nitrogen-, potassium-, and phosphorus-deficient corn leaves. Consider first the three in a group. The right leaf was deficient in nitrogen. Note that the yellowing started at the tip and proceeded down the midrib, while in the potassium-deficient leaf in the center the yellowing started at the tip and moved down the edges of the leaf, leaving the midrib area green. The left leaf was normal. The inset shows a section of normal and phosphorus-deficient leaves. Note the reddish purple edge on an otherwise dark-green leaf.

Fig. 1b. A potassium-deficient corn plant. Compare with Figs. 1a, 2, and 16. (Photo—Coke Oven Ammonia Research Bureau)

Fig. 2. A field of corn suffering from serious nitrogen starvation. The entire field had taken on a light green appearance, and the yellowing of the leaves in the characteristic nitrogen deficiency pattern had developed to the third leaf. Note the red color at the base of the stalks. Tissue tests showed no trace of nitrate nitrogen in the stalk. This condition has been commonly called "dry weather firing."

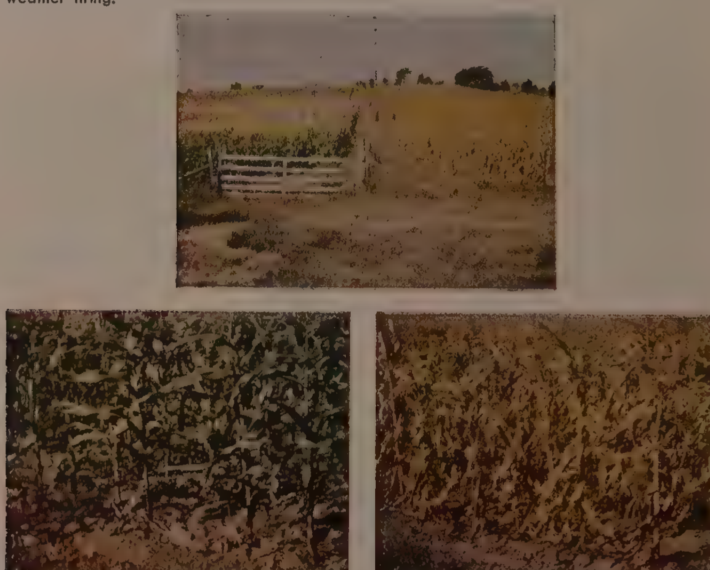

Fig. 3. Two fields of corn on similar soil on the same farm in Cass County. In the left field, the corn was planted after clover which had been pastured and manured before the land was plowed. Although the picture was taken after a prolonged drought, there was not a sign of dry weather firing. As shown in the close-up view, even the lowest leaves were normal in color and the set of ears gave promise of a good crop. In the other field, the corn was fired to the

Fig. 4a. Corn following wheat with no legume in the rotation, on the Ferden rotation experiment. A very good illustration of nitrogen deficiency. The tissue test showed no trace of soluble nitrogen in the stalks on the day the picture was taken.

Fig. 4b. Corn following one year of alfalfa on the Ferden rotation experiment. Not a trace of firing is apparent. The tissue test showed the stalks to be high in soluble nitrogen on the day the picture was taken.

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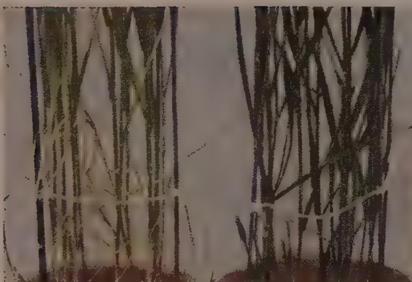
tassel and the set of ears was very light. The difference in the two fields was largely one of nitrogen supply as in the right field, corn had followed corn with no manure applied. It is true that the right field was planted a few days earlier, but even so, maturity would not have been reached so early as August 23, the date on which the picture was taken. In fact, late planting should have tended to penalize the other field.



(left) Fig. 6. When oats become deficient in nitrogen they fire in a manner not unlike that of corn. The plants in these two pots received all the water they needed. In the right pot they received also all the nitrogen they needed. Even the lowest leaves were green. The plants in the left pot were starved for nitrogen. Note the general light-green color of the upper leaves and the yellow, dried-up lower leaves. This condition occurs very often in the field, and it is not "just dry weather firing."

(right) Fig. 7. Wheat grown in the field on Brookston clay loam soil. Left bunch was deficient in nitrogen. Notice the yellow, dried-up lower leaves. The nitrate test showed that the plants did not contain soluble nitrogen. The test showed the right-hand plants to be high in soluble nitrogen.

Fig. 8. Nitrogen deficiency is common in soybeans. Note that the yellowing of the left, nitrogen-deficient leaf is uniform over the entire leaf. The veins do not remain green as they do where there is a lack of manganese in the soil.

(left) Fig. 9. A lack of available nitrogen quickly affects the appearance of sugar beet tops. The left beet was grown in Miami loam soil which had received a fertilizer without nitrogen. Note the light-green color and the flattened-out position of the leaves, characteristic of nitrogen starvation. The beet on the right was treated in a manner similar to the other except that it received an ample supply of nitrogen.

(right) Fig. 10. Alfalfa furnishes nitrogen for sugar beets. In pot 1, beets were grown after corn which had followed alfalfa, while in pot 2 the beets had followed immediately after the alfalfa. Note the greater top growth and the dark-green color. Note also the fact that the lower leaves on the plant in pot 2 were becoming yellow at the time the picture was taken. Evidently the nitrate supply was becoming exhausted. In pot 6 the beets were grown after wheat without a legume in the rotation.

Fig. 11. When cucumbers are deficient in nitrogen, the oldest leaves are the first to lose their chlorophyl. The yellowing is uniform over the entire leaf. The two rows on the left received only the nitrogen in 1000 pounds of 2–16–8 fertilizer. The green color had faded from all the leaves, and the oldest ones had died. The two rows on the right had received an additional application of nitrogen in the form of ammonium nitrate. That it was insufficient to last until the picture was taken is indicated by the yellowing of the oldest leaves. Another application was needed at that time.

Fig. 12. The color of coleus plants may be varied by regulating their supply of soluble nitrogen. These two plants were grown on Miami loam soil, into which had been mixed a large quantity of chopped straw. Soluble nitrogen in the form of ammonium nitrate had been added to the left pot. Note the much darker red color. In the other pot the bacteria, in decomposing the straw, had used up so much nitrogen that the plant had been starved. The tissue test showed nitrate to be plentiful in the leaves of the left plant but entirely lacking in the right-hand plant.

(left) Fig. 14. An ample nitrogen supply is essential for pasture grasses. Note dark color of the grass in the spots where urine has been voided by the animals.

(right) Fig. 15. Peaches are very sensitive to nitrogen deficiency. Normal leaves are here compared with those which are nitrogen-deficient. Note the light-green color and the red spots on the leaves. (Photo—Wesley P. Judkins, Ohio Agricultural Experiment Station)

Fig. 16. A phosphorus-deficient corn plant.

Fig. 17. Alfalfa is very sensitive to a deficiency of phosphorus. These plots were located on Miami loam soil on the Dilman farm near Cass City. The alfalfa plants on the left plot had not yet reached the height of the grain stubble. The difference in growth was due to the application of superphosphate on the right-hand plot.

(left) Fig. 18. Sugar beets deficient in phosphorus grow slowly and are very dark green in color during early growth. The leaves may be fringed with red.

(right) Fig. 19. Phosphorus-deficient sugar beets become light green in the later stages. The symptom at that time resembles that of nitrogen deficiency. The green-tissue test may be necessary to avoid confusion.

Left—Only nitrogen applied.
Right—Phosphorus and nitrogen applied.

(left) Fig. 20. Bean leaves turn yellow when phosphorus deficiency becomes serious. The green veins would not indicate manganese deficiency because of the lack of uniformity in the yellowing of the other leaflets. The left leaf was from a normal plant.

(right) Fig. 21. Tomato leaflets. At the right is the end leaflet from a lower leaf of a seriously nitrogen-starved plant. Note the prominent purple veins on an almost yellow leaf. The center leaflet is from a similar position on a phosphorus-starved plant. Note the purple color of the entire under surface of the leaflet. The left leaflet was from a normal plant.

Fig. 22. Barley, potassium-deficient on the left and normal on the right. The deficient plants were taken from unfertilized plots on Hillsdale sandy loam. The lower leaf of each plant had turned yellow from the tip for a distance about half its length. There seemed to be a tendency for the yellowing to proceed faster along the leaf edges than along the midrib. This tendency seems, however, to be less pronounced than it is with corn. The tissue tests, illustrated in the picture, showed that potassium was high in the normal plants and low in the deficient plants.

(left) Fig. 26. Alfalfa and clover leaves from a phosphate-treated plot on Napanee silt loam soil. Unmistakable symptoms of potassium deficiency are the yellow-edged leaflets with white dots scattered through the yellow area. In this particular field the symptoms of potassium hunger occurred on only the phosphate-treated plot.

(right) Fig. 27. Tissue-test results obtained on plants shown in Fig. 26. Left vial illustrates the potassium test on plants from the phosphate-treated plot. Notice that the black line is easily visible *through* the vial. This indicates a small amount of precipitate and a low test. Apparently the increased growth caused by the phosphate had rather completely exhausted the supply of available potassium in the soil. The right vial illustrates the potassium test made on the plants from the unfertilized plot. Apparently there was more potassium available to the plants than on the phosphate-treated plot, as the black line is less easily visible through the vial. The center vial illustrates the very high potassium test obtained on plants grown on the potash-treated plot. The plants were getting all the potassium they needed.

Fig. 28. Bean leaves yellowed from deficiency of manganese and potassium compared with a normal leaf. The left leaf was normal. The center leaf was deficient in potassium. It yellowed first at the tips and along the edges of the leaflets. Notice also the crinkled appearance, brought about by the continued growth of the interior portions of the leaflets, after growth had ceased along the edges. The right leaf was deficient in manganese. Notice the uniformity of the yellowing, with the veins remaining green.

(left) Fig. 29. Beans on Miami loam on the Miller farm in Clinton County. Where potash was an ingredient of the fertilizer the plants were normal, but where only phosphate was applied there was more yellowing than on unfertilized plots.

Left —0–20–0, 240 pounds per acre.
Right—4–16–8, 300 pounds per acre.

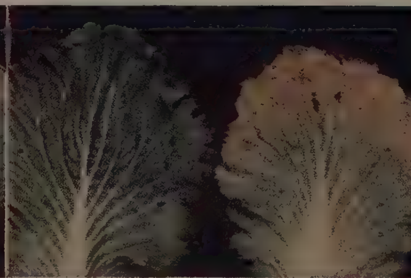
(right) Fig. 30. Soybean leaves, potassium-deficient on the right and normal on the left.

(left) Fig. 32. Cowpea leaves, potassium-deficient on the left and normal on the right.

(right) Fig. 33. Potato leaves from plants grown in greenhouse pots. Left leaf came from a plant which had received a complete nutrient solution while the right one was from a plant which had received all nutrients except potassium. The yellowing had started at the tips and around the leaflet edges. Necrosis had taken place around the edges at the time the picture was taken.

(left) Fig. 34b. Tomato leaves showing both potassium and phosphorus deficiency. Upper left hand leaf was from a potassium-deficient plant, growing where the supply of nitrogen had been low. The upper right hand leaf was from one deficient in potassium but where the supply of nitrogen had been very high. Note the white dots. The lower left hand leaf was normal whereas the two at the lower right were deficient in phosphorus. Note the intense purple color of the lower side of the leaf, including the veins.

(right) Fig. 35. A cucumber leaf deficient in potassium. Note the yellowing is distinctly around the edges of the leaf. The appearance presents a striking contrast to that of a leaf deficient in nitrogen where the yellowing is uniform over the entire leaf. In both cases the oldest leaves are the first ones affected.



(left) Fig. 36. Cabbage leaves, normal on the left and potassium-deficient on the right.

(right) Fig. 37. Celery cabbage leaves, normal on the left and potassium-deficient on the right.

Fig. 38. Cineraria plants, potassium-deficient on the left, normal in the center, and nitrogen-deficient on the right. It is very important that the foliage of flowering plants be of a normal color. Nutrient levels must be properly maintained if healthy plants are to be grown.

(left) Fig. 39. Stocks are sensitive to potassium deficiency. This plant had been very seriously injured by the deficiency. Note the lower leaves yellowed from the tip back along the leaf edges. Only the very newest leaves were still normal in appearance when the picture was taken.

(right) Fig. 40. Geranium leaves deficient in potassium.

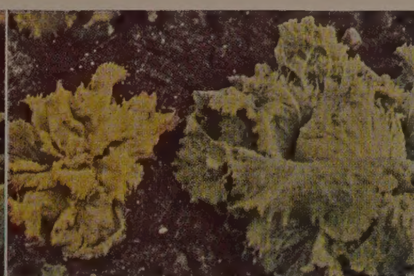
Fig. 41. Oats deficient in manganese may be a complete failure because of the physiological "disease" known as "grey speck." It starts as a grey, oval-shaped spot on the edge of the leaf some distance back from the tip. The center leaf shown here was typical of the first stage of grey speck while the lower leaf was typical of the later stage, after the spot had enlarged to take in the full width of the leaf for 2 or 3 inches. The top leaf was normal. The grey of the early stage changed to yellow in the later stage. Notice that the tip of the leaf remained green. This characteristic makes it easy to distinguish manganese deficiency from nitrogen deficiency.

Fig. 46. Garden beans on the Martin Pett farm near Bay City. The left row of beans (the very first row was beets) was sprayed with manganese sulfate at the rate of 5 pounds per acre. The other three rows were not sprayed.

Fig. 47. Sugar-beet leaves deficient (1) in manganese, (2) in potassium, and (3) in nitrogen. The number 4 leaf was normal. Compare the uniform yellowing of the manganese-deficient leaf, with prominent green veins, with the strikingly different pattern of yellowing on the leaf deficient in potassium. Nitrogen deficiency differs from manganese deficiency in that the veins do not remain green when the leaf is nitrogen-deficient.

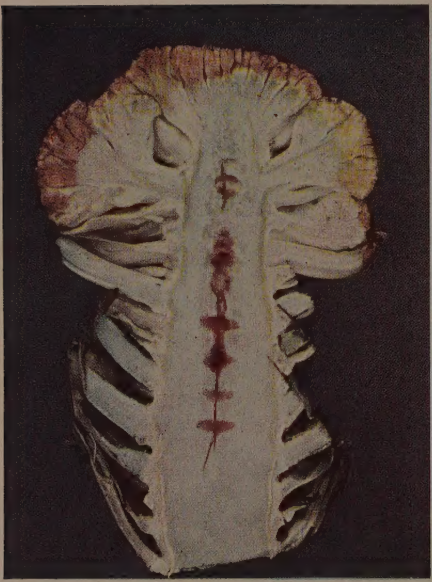

(left) Fig. 53. Red beet deficient in boron. Notice the cankers where the broken-down areas of tissue extended through the epidermis.

(right) Fig. 54. In these cooked slices of boron-deficient red beets, the internal black spots were even more prominent than before cooking. This was because the cooking had removed the red pigment but had not affected the black corky tissue.

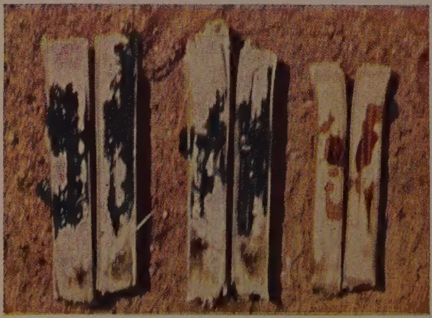
(left) Fig. 55. A spinach plant deficient in boron. Note the many small leaves, most of them twisted and developed more on one side than on the other. Refer to Fig. 56.

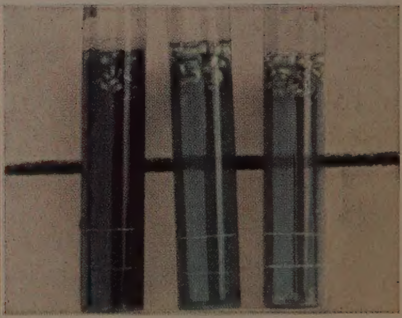
(right) Fig. 58. Head lettuce is very sensitive to boron deficiency. The well-formed, normal head on the right was grown on a plot which received 10 pounds of borax per acre. The plant on the left had failed to head. The center leaves remained small and were deformed and black.



(left) Fig. 59. Cauliflower is very sensitive to boron deficiency. Note the broken-down center of the stalk and the brown color of the edible portion of the head. (Photo—E. K. Walrath, Eastern States Farmers Exchange)

(right) Fig. 60. Celery deficient in boron develops the disorder known as "crack stem." This is a typical example. (Photo—E. K. Walrath, Eastern States Farmers Exchange)





(left) Fig. 67. Nitrate tests made on green corn plants. The brown color means a low test while the blue color indicates a high test.

(right) Fig. 68. Tissue-test results for phosphorus on alfalfa plants grown on experimental plots. Left vial illustrates the result of a very high test. The plants were grown on a plot which received phosphate fertilizer. The right vial illustrates the result obtained by testing plants from an untreated plot. The test was low. The black line was just barely visible through the solution. The center vial illustrates the result obtained by testing plants from a plot which had received potash fertilizer. The test was very low. Notice that the black line is easily visible through the solution.